USING VALUE-FOCUSED THINKING TO EVALUATE THE PRACTICALITY OF POROUS PAVEMENT PARKING AREAS ON AIR FORCE INSTALLATIONS

THESIS

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AFIT/GEM/ENV/06M-01

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AFIT/GEM/ENV/06M-01

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THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

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March 2006

AFIT/GEM/ENV/06M-01

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AFIT/GEM/ENV/06M-01

Abstract

Natural runoff processes have been altered by urban development; impervious surfaces (rooftops, highways, parking areas) and their associated stormwater systems channel runoff from a vast area into one concentrated outflow. This stormwater runoff can cause erosion, flooding, landslides, and significant damage to aquatic ecosystems. Runoff from highways and parking areas has also been shown to contain high levels of suspended solids, heavy metals, and hydrocarbons. Porous pavements allow infiltration of water through typically impervious surfaces, reducing stormwater volumes and acting as a pollutant filtration system.

Since there is currently no methodology for Air Force decision-makers to compare conventional and porous pavements, a model was created using Value-Focused Thinking (VFT) to evaluate different paving options. Four porous paving alternatives were compared against two conventional paving alternatives at three separate geographic locations. These alternatives were scored using a total of 12 evaluation measures that were identified as important to the pavement selection process. Structural turf, a porous alternative, was found to be the best option for northern tier locations, while conventional asphalt was the best choice for central and southern areas. VFT was also shown to be an effective methodology for comparing conventional and porous paving alternatives, objectively weighing economic costs against environmental considerations.

Acknowledgments

I'd like to give special thanks to my advisor and committee chairperson, Lt Col Ellen England, for giving me the inspiration to investigate green technologies and the support and guidance to succeed in this research endeavor. Besides commenting on my numerous thesis drafts, her gentle reminders to continually stay on course ultimately helped avoid a lot of stress as I finished my time here at AFIT. I'd also like to thank my committee co-chairperson, Lt Col Jeffery Weir, for his expertise in the Value-Focused Thinking methodology and his assistance in the shaping of my model to evaluate porous paving technologies. Lastly, thanks to Dr. Charles Bleckmann for taking the time to look over and offer feedback on my thesis drafts and presentations.

1Lt Christopher D. Bulson

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USING VALUE-FOCUSED THINKING TO EVALUATE THE PRACTICALITY OF POROUS PAVEMENT PARKING AREAS ON AIR FORCE INSTALLATIONS

1. Introduction

1.1. Overview

The runoff of surface water after precipitation events is a natural occurrence in our environment; the soil absorbs what it can and the rest of the water finds its way to groundwater or surface water systems such as stream or river channels. However, natural runoff processes have been altered substantially by urban development. The growth of urban areas results in a decrease in pervious surface area (grasses or soils) that normally absorbs a large amount of precipitation. Impervious surfaces (rooftops, highways, parking areas) and their associated stormwater systems channel runoff from a vast area into one concentrated outflow. During peak outflows, this stormwater runoff can cause erosion, flooding, landslides, and significant damage to aquatic ecosystems (Booth & Leavitt, 1999). Runoff from highways and parking areas has also been shown to contain high levels of suspended solids, heavy metals, and hydrocarbons (Pagotto et al, 2000).

Porous pavements differ from traditional pavements in that they allow the infiltration of water through typically impervious surfaces and thus reduce stormwater volumes (Brattebo & Booth, 2002). Porous pavements have also been shown to act as filtration systems, intercepting large percentages of pollutants that would have normally been carried off as runoff (Pagatto et al, 2000). Porous pavements can also offer highway

safety benefits by reducing splashing and hydroplaning during rainfall events (Pagatto et al, 2000). Aesthetically, porous pavements can provide decorative designs and acoustically quieter highways (Golebiewski et al, 2003).

1.2. Background

According to the Code of Federal Regulations (40 CFR §122.26(b)(13)), stormwater is defined as "storm water runoff, snow melt runoff, and surface runoff and drainage." Problems caused by stormwater are growing throughout the United States and the continual spread of impervious surface area is mainly to blame. In *Porous Pavements*, Bruce Ferguson estimates that there is an increase of 250 square miles of pavement each year in the United States alone.

Current stormwater regulations stem from the EPA's efforts to comply with the Water Quality Act of 1987 by controlling stormwater discharges for industrial areas and large municipalities (populations greater than 100,000). Today's rules have been expanded to include smaller municipalities (less than 100,000 people) and small construction sites (1 to 5 acres). These areas must acquire a National Pollutant Discharge Elimination System (NPDES) permit and must also use best management practices to maintain acceptable water quality levels (Sullivan, 2003). A best management practice can be defined as "any method believed to be effective in preventing or reducing pollution or otherwise protecting the environment" (Ferguson, 2005).

Many best management practices for improving stormwater quality and reducing quantity are in use today. Green roofs, grass swales, bio-retention cells, and porous pavements are just a few methods available to reduce stormwater impacts (EPA, 2000). Although in existence since the 1970s, porous pavements are still not a widely used

method of paving in this country. The most likely reasons for this limited use is the lack of experienced contractors able to install and maintain porous systems, and the higher installation and maintenance costs compared to traditional asphalt or concrete paving.

Unfortunately, the reluctance to purchase a more costly, unfamiliar paving method has kept porous pavements from widespread use and acceptance here in the United States. However, international efforts have validated the effectiveness of porous pavements in drastically increasing infiltration and groundwater recharge, improving water quality, reducing road noise, and improving driving conditions during inclement weather (Ferguson, 2005).

According to the Air Force's Sustainable Development Policy letter of December 2001, the Air Force will use sustainable development concepts wherever consistent with meeting cost and mission needs (Robbins, 2001). This policy directly applies to improving stormwater management for two reasons. First, one of the sustainable development goals is to conserve water through the reduction, control, or treatment of site runoff. Secondly, the AF is using the Leadership in Energy and Environmental Design (LEED) criteria to determine the degree to which sustainable design principles are being applied. Under the LEED rating system, points are awarded to sites using porous pavements to reduce the rate and quantity of stormwater leaving the site (USGBC, 2002).

1.3. Problem Identification

Although the Air Force is committed to applying sustainable development concepts, military decision-makers are still largely unaware of how porous pavements may contribute to these goals by improving stormwater quality and quantity on Air Force installations. The purpose of this study is to identify the environmental and economic

tradeoffs associated with using various porous paving options for Air Force parking areas. This research will categorize these tradeoffs, building a model to assist the military decision-maker in thoroughly evaluating all paving options before selecting the best choice for his or her installation.

1.4. Research Questions

In order to create an effective decision-making model, the following research questions will be addressed by this study:

1. What are the characteristics, benefits, and disadvantages associated with different types of porous pavements?
2. Where have porous pavements been used successfully in the past?
3. What are the environmental and economic impacts of stormwater discharges from urban areas?
4. What is the appropriate methodology for choosing to construct a parking lot from a porous pavement rather than a conventional pavement?
5. What is important to Air Force decision-makers when selecting paving options?

1.5. Research Approach

Evaluation of different paving methods may be difficult because each has differing strengths and weaknesses. In order to compare paving options on the same scale, this research will create a decision-making tool that will give a military decision-maker the ability to use his/her own values, risk preferences, and objectives to determine which paving option is best for his/her situation. A methodology capable of providing the necessary insight into this decision-making process is called Value-Focused Thinking

(VFT). VFT is a strategic, quantitative approach to decision-making that uses specified objectives, evaluation measures, and value hierarchies (Kirkwood, 1997). Value-focused thinking follows a sequence of five activities when dealing with decision problems: recognize a decision problem, specify values, create alternatives, evaluate alternatives, and select an alternative (Keeney, 1992). The VFT sequence differs from the traditional alternative-focused approach because the traditional approach looks for alternatives before considering values. Ralph Keeney describes values as "principles used for evaluation."   Evaluation measures are determined to effectively score these values for each alternative. A single-dimensional value function will then be created to compare each alternative on the same scale. This research will use VFT to create a model for military decision-makers to use when selecting pavement types for parking lots on their particular installations.

Research questions 1 and 2 will be addressed by examining case studies of porous pavements. The past performance of existing porous pavement applications offers much insight into the durability, maintenance costs, and problems associated with these pavements. By analyzing specific applications, potential benefits and drawbacks may be validated. Question 3 will be addressed through the examination of current literature. The VFT model will be used to address questions 4 and 5.

1.6. Scope

Although there are many varieties of porous pavements, this research will be restricted to the following categories: paving stones, structural turf, porous asphalt, and porous concrete. These porous pavement categories will be evaluated against traditional asphalt and concrete pavements (the most commonly used materials for surface

covering). This model will use the decision-maker's values to compare the economic and environmental benefits of porous and non-porous paving techniques and also have the flexibility to be able to be used anywhere by evaluating key site conditions (location, climate, etc.) and incorporating those aspects into the pavement selection criteria. One limitation of this model is that the weights used in this model are subjective and may be different from the weights of the end user. In order for this model to be universally applied, it must be understood that the weights need to be re-evaluated by each decision-maker to fit the model to their specific situation/conditions.

1.7. Significance

This research is justified by the Air Force's Sustainable Development Policy that seeks to employ technologies and practices that contribute to a greater environmental good. By using porous pavements for roadways and parking areas, the Air Force could significantly reduce stormwater volumes and runoff pollutants from its installations. This research will identify additional economic costs associated with these paving options but also show those costs to be offset by measurable environmental benefits. The true significance of this research will be in increasing the awareness of our military decision-makers for the range of options they have when designing, constructing or replacing an area of pavement on their installation.

1.8. Summary

As populations continue to grow, the amount of impervious surface area in this country will increase accordingly. This impervious area will continue to block natural groundwater recharge, heat up our cities, and collect oil and pollutants from our

automobiles before flushing them into watersheds in concentrated bursts. These bursts of precipitation outfall can erode streambeds, cause landslides, and poison aquatic ecosystems. Many communities are doing their part to improve their stormwater management (Ferguson, 2005) and the Air Force should also seek all opportunities to do the same. This model will show porous pavements to be an effective substitute for conventional methods, giving Air Force decision-makers the awareness to help our bases leave a smaller footprint on the environment.

2. Literature Review

2.1. Overview

The purpose of this chapter is to provide an in-depth review of all applicable literature, theory, and current research related to stormwater issues, conventional and porous pavement use, and particular decision analysis strategies. This literature review will be divided into three major sections: stormwater, pavements, and value-focused thinking (VFT). The stormwater section will cover stormwater problems, management practices, and current regulations. The pavements section will review the functionality, benefits, disadvantages, and costs associated with conventional and porous pavements. The VFT portion will describe the process and delineate procedures used during the application of VFT.

2.2. Stormwater

As shown in Figure 1, the natural hydrologic cycle consists of precipitation, groundwater recharge and flow, runoff to surface waters, evaporation, and evapotranspiration (UFC, 2004). The processes behind this cycle have not changed with society's development of natural areas, but there are some differences between a natural hydrologic cycle and a post-development cycle (as shown in Figure 2). Most notably are the increase in surface water runoff and the decrease in groundwater infiltration in developed areas due to impervious surfaces. Precipitation that becomes groundwater recharge in the natural environment is converted to runoff in the developed environment.

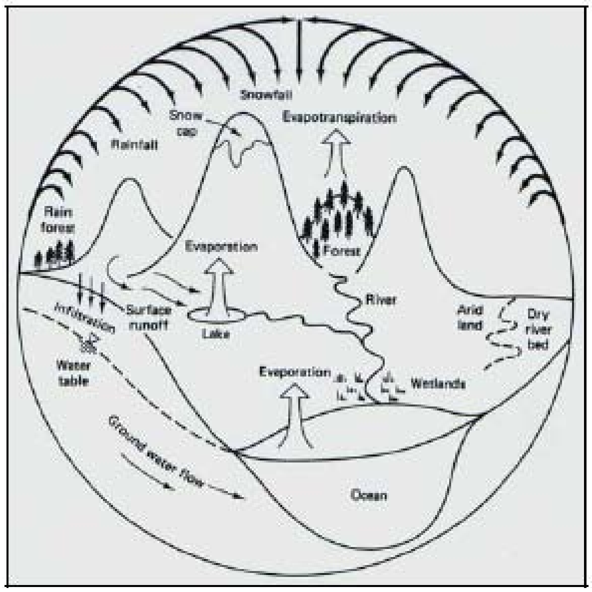


Figure 1. Natural Hydrologic Cycle (UFC, 2004). This cycle involves several processes including precipitation, infiltration, groundwater flow, and surface runoff.

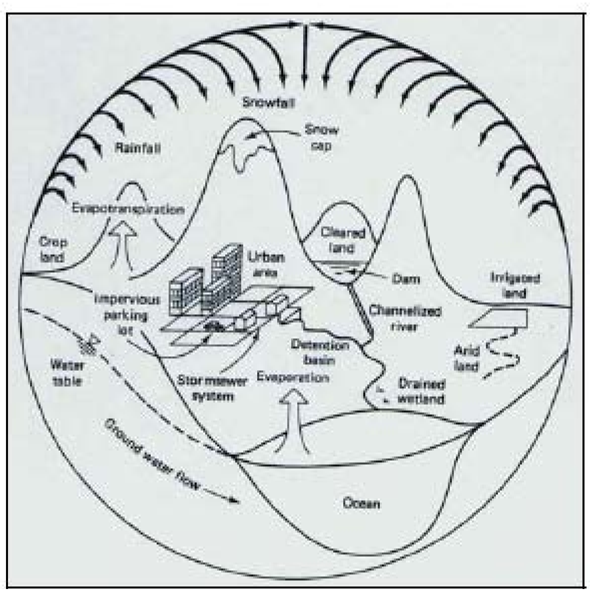


Figure 2. Post-Development Hydrologic Cycle (UFC, 2004). The runoff and infiltration portions for the cycle are interrupted by the growth of urban areas.

Urban areas use conventional stormwater systems to perform the primary drainage function by collecting and routing runoff to streams or treatment facilities in order to avoid urban flooding (Grigg, 2003; EPA, 2000). The problem with these systems is that they allow the runoff from a large area to be concentrated into one large stormwater outflow. Having large peak volumes from these outflows can have several impacts on the receiving water systems including erosion, flooding, landslides, and significant damage to aquatic ecosystems (Booth & Leavitt, 1999). Runoff from highways and parking areas has also been shown to contain high levels of suspended solids, heavy metals, and hydrocarbons (Pagotto, 2000).

2.2.1. Problems

For many communities, urban sprawl is causing the reduction of green spaces, the increase in the dependence on automobiles, and the widening of urban fringes (EPA, 2000). The expansion of these urban fringes affects the quantity and quality of stormwater produced by these areas because of the associated increases in impervious surface area and the removal of wetlands and other natural areas. Most of this impervious area is dedicated solely to automobile traffic in the form of roads and parking areas (Ferguson, 2004). Estimates show impervious area increasing at a rate of 250 square miles per year in the US alone (Ferguson, 2005). According to the 2000 EPA report, *Low Impact Development*, water quality is drastically reduced in streams, lakes, and wetlands when the amount of impervious surface area upstream is greater than 10% (EPA, 2000).

Stormwater quality is affected by many factors and processes. Novotny (1984) classified non-point stormwater pollutants into the following categories: wet and dry atmospheric deposition, street refuse deposition (including litter, street dirt and organic residues), traffic emissions and impact, urban erosion, and road deicing. While these categories describe the numerous possible sources of stormwater pollution, the concentrations of these urban pollutants may vary drastically in different areas of the country. For example, urban areas with higher automobile traffic or strong industrial centers may experience more stormwater pollution than smaller cities with light traffic patterns and less industry. Due to these area differences, regulating stormwater quality has been difficult.

The increase in impervious surface has also contributed to what is known as the urban heat island effect (Ferguson, 2005). The urban heat island effect is the phenomena where urban areas tend to heat up faster, and stay warmer longer, than surrounding rural areas. This effect is caused by impervious surfaces collecting solar radiation which heats up the air above the surface causing higher temperatures in urban areas during the day. Urban areas may be up to 8^{o}F warmer than surrounding rural areas (Ferguson, 2005). These impervious surfaces also store the sun's energy during the day and then release it at night causing what has been called the nocturnal heat island (Asaeda, 2000).

2.2.2. Management Practices

To combat the problems of urban generated stormwater runoff, low impact development strategies have been employed. Low Impact Development (LID) is described as a design strategy that attempts to mimic the natural drainage functions

(storage, infiltration, and groundwater recharge) of the pre-developed landscape (EPA, 2000). The Unified Facilities Criteria (UFC) manual, *Design: Low Impact Development*, states a similar definition but focuses on natural resource protection and compliance with regulations (UFC, 2004). Five key elements of LID are shown in Figure 3.

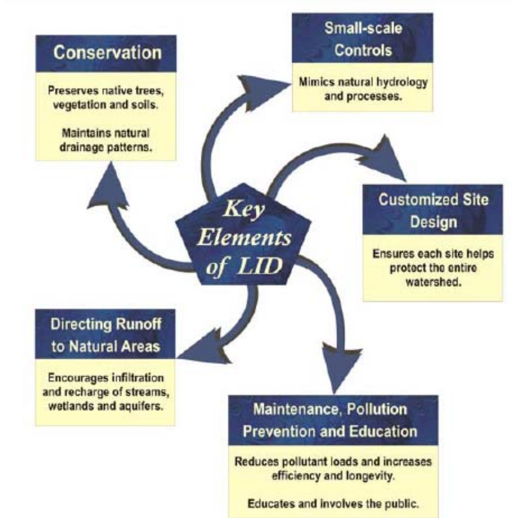


Figure 3. Key Elements of Low Impact Development (UFC, 2004). The elements of LID provide numerous methods to help mimic and maintain natural hydrologic patterns.

The main idea behind LID is to use smaller design controls to help manage stormwater on the site rather than using large conventional facilities (UFC, 2004). The stormwater can be thought of as a commodity and every effort should be made to keep the water on site (Ciccocioppo, 2005). Porous pavements, green roofs, bioretention areas, grass swales and other means of transferring stormwater across pervious surfaces are all valid LID techniques (EPA, 2000 & UFC, 2004). Porous pavements are pavements which allow water to infiltrate the surface, reducing stormwater runoff. Green roofs can also reduce runoff by intercepting precipitation in the growing mediums (grasses and plants) placed over the structural members. Bioretention areas and grass swales are areas of natural vegetation whose purpose is to temporarily store runoff water

and also allow it to infiltrate the soil.   Figure 4 shows various treatment options and their associated capabilities for flow volume and particle size.

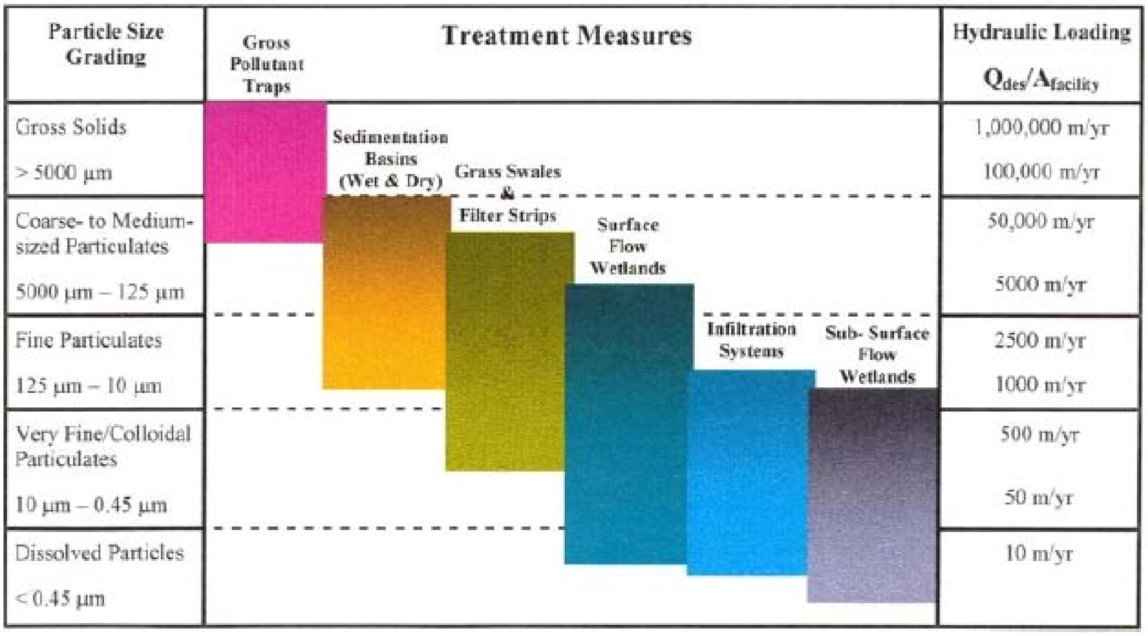


Figure 4. Effectiveness Comparison of Various BMPs (UFC, 2004). Effective treatments are available for a wide range of hydraulic flows.

2.2.3. Regulations

In 1972, the Clean Water Act directed that no unpermitted point source pollution would be allowed to enter the navigable waters of the United States. However, stormwater quality and quantity has been difficult to regulate because of the various non-point sources of pollution that contribute to stormwater flows. The Water Quality Act of 1987 was the first federal requirement for the creation of specific regulations to control stormwater discharges. In response to this Act, the EPA disseminated rules to govern stormwater discharges originating on industrial sites and municipal separate storm sewer systems (MS4s) supporting more than 100,000 people (Sullivan, 2003).

Today's state and local stormwater rules are guided by the EPA's National Pollutant Discharge Elimination System (NPDES) Phase II stormwater regulations. NPDES Phase II requires smaller MS4s (populations less than 100,000 people and deemed an "urbanized area" by census data) and construction sites between one and five acres to obtain a permit and implement a stormwater management plan that uses Best Management Practices (BMPs) to control stormwater runoff (Sullivan, 2003; Smith, 2003). The LID strategies listed in the previous section can all be used to help with these BMPs but MS4s should choose ones that best meet the goals of their specific stormwater control programs (Smith, 2003).

The Air Force is required to follow the Phase II requirements when a particular base is deemed to be an MS4. In order to fulfill the Phase II requirements, a base will need to produce a Stormwater Pollution Prevention Plan (SWPPP) identifying potential pollutants and what steps will be taken to reduce those pollutants (Sullivan, 2003). The seven step process created by the EPA to guide the development and implementation of SWPPPs is shown in Figure 5. The SWPPP is the only source of specific regulations regarding the quality and quantity of stormwater leaving the installation. After the base creates the SWPPP, it is forwarded to the appropriate state or federal agency for review and approval. Once approved, the base is only committed to the measures set forth in its SWPPP.

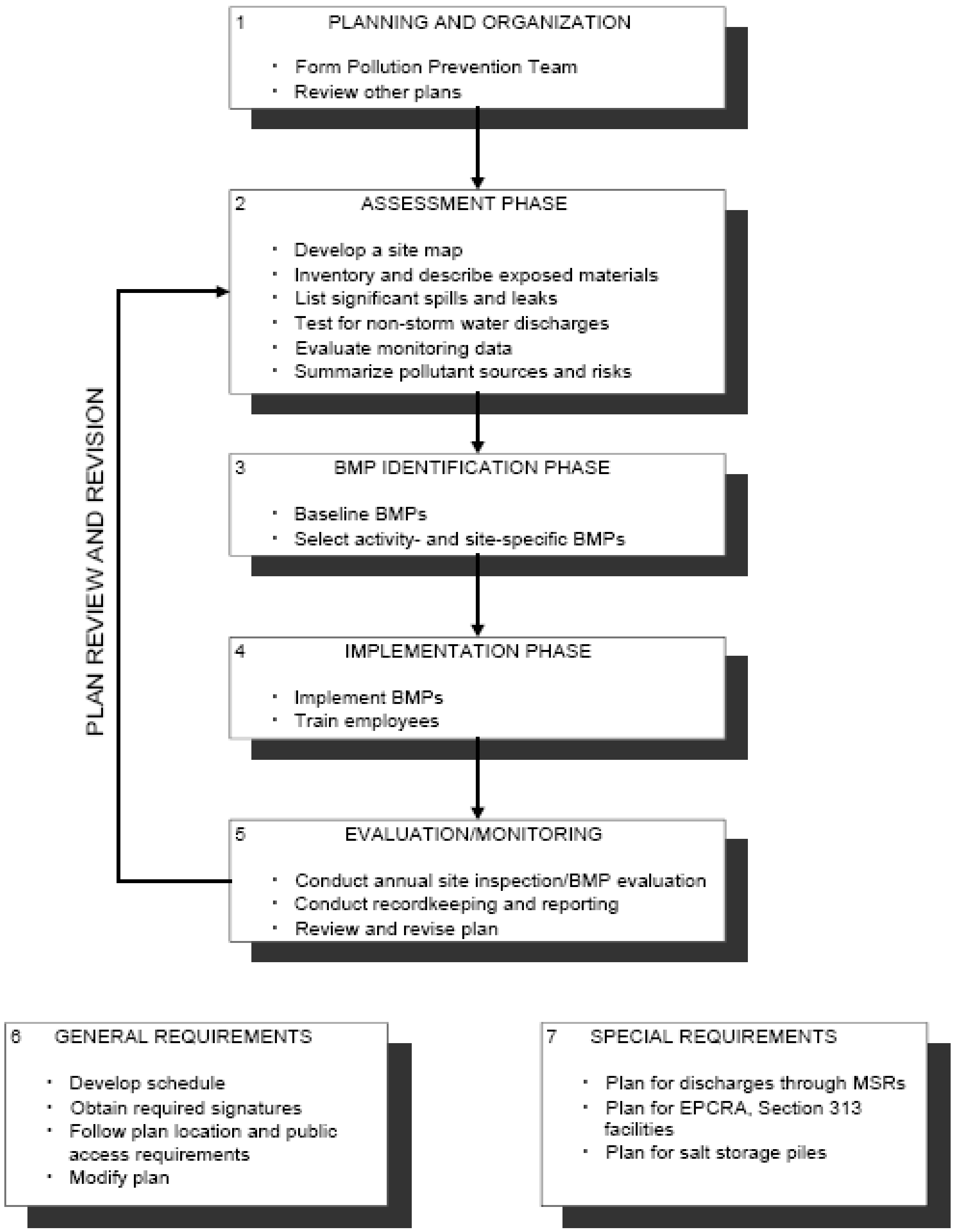


Figure 5: Stormwater Pollution Prevention Plan (SWPPP) Flowchart (EPA, 1992). A SWPPP is developed through seven steps.

2.3. Characteristics of Conventional Pavements

For the purposes of this thesis, the term “conventional pavement” will refer to impervious Hot Mix Asphalt (HMA) and concrete. Today’s roads and parking areas are primarily constructed from these two materials. Both materials block surface water from

infiltrating the soil. Instead of contributing to local groundwater recharge, any precipitation that falls on these surfaces will be diverted to downstream stormwater outflows. This section will offer a brief description of the structures and properties of these two pavement types.

HMA is a mixture of aggregates (crushed stone and sand), fillers (cement and stone dust), and binder (asphalt cement). As shown in Figure 6, machines lay and roll this mixture while hot, which then creates a waterproof, durable surface that is ready for traffic as soon as it cools (UFC, 2001). The supporting layers for the HMA mix are the subgrade (underlying soil layer) and base/intermediate courses (crushed stone layer beneath the HMA mix). These layers need to be properly constructed and compacted to allow for the appropriate structural support of the HMA layer, and drainage of the base course (UFC, 2004). Costs for conventional asphalt can be estimated from $0.50 to $1 per square foot (EPA, 2000). Due to its low initial costs, asphalt is typically the preferred method of paving in the US. Asphalt pavements make up 75% of all of the paved surfaces in this country (Ferguson, 2005).

Figure 6: HMA Application (CA DOT, 2006). After HMA is laid, it is then rolled to produce a dense, smooth surface.

Concrete is made of fine and coarse aggregates and a "paste" comprised of Portland cement and water (PCA, 2005). Once mixed, the water begins to react with the cement and the mix becomes increasingly stiffer with time. The concrete mix is then poured within forms to harden into the appropriate shape. Rebar (structural steel members) is placed within the mix for added strength. After the mix is placed in the appropriate form (for roads, walls, etc.), it requires time to cure. During the curing process, the goal is to keep the surface of the concrete moist by sprinkling with water or by overlaying with wet burlap or cotton sheets. The longer the surface is kept moist, the more strength the concrete will gain (PCA, 2005). In order to achieve designed strengths, concrete ingredients must also be mixed in precise proportions as shown in Figure 7. Fully hardened concretes usually have strengths of approximately 3500 pounds per square inch (Ferguson, 2005).

Figure 7: Concrete Components (PCA, 2005). Maintaining proper proportions of ingredients will help ensure high strength.

2.4. Porous Pavement Overview

The purpose behind porous pavements is to allow water to infiltrate what is normally an impervious surface. Converting impervious surfaces to pervious ones can lead to a significant reduction of an area's runoff. Wanielista (1986) suggested that residential runoff could be reduced by 35% if driveways were constructed of highly pervious materials. Also, when properly installed, porous pavements have similar strengths, durability, and maintenance needs as conventional pavements and can mimic the natural hydrologic functions of the site (Schueler, 1987). As shown in Figure 8, typical porous pavements consist of a pervious surface layer, a reservoir structure (base course), a filter fabric (geotextile membrane), and a level sub-base (subgrade) (Wilson, 2004).

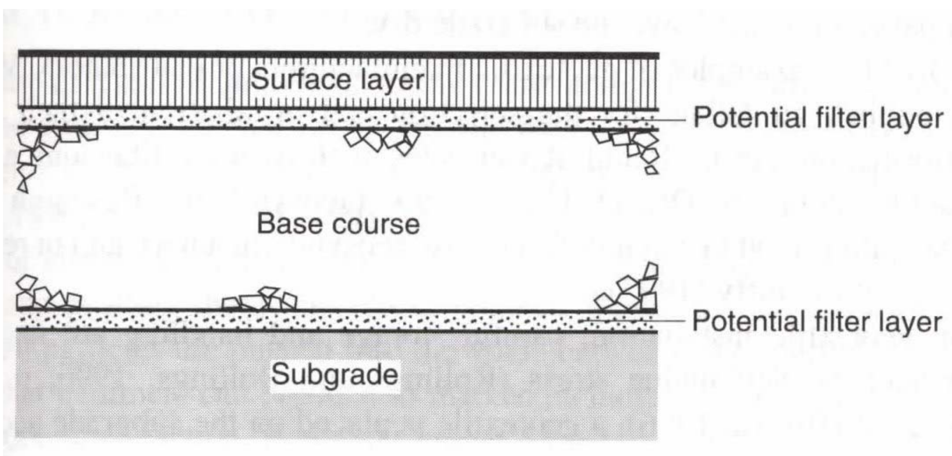


Figure 8: Typical Porous Pavement Cross-section (Ferguson, 2005). Pavements will generally have three main layers and geotextile filters.

Porous pavements have had some historical setbacks in terms of their success in the United States. Particularly, most porous pavement applications have been known to experience a failure rate of 75% in the first two years (EPA, 1999). The Air Force, in particular, has had some negative experiences with failed porous pavement applications.

During the early 1990’s, Malmstrom Air Force Base (AFB) installed a porous friction course overlay on its primary runway. Due to a poor binder mixture, areas of aggregate with limited binder eventually came loose resulting in foreign object damage on several aircraft engines (Murray, 2006). However, one faulty design/installation should not affect the Air Force’s ability to consider this technology when installing new pavements.

2.4.1. Costs

In general, porous pavements are thought to be more costly than conventional methods. While the per square foot cost of porous pavements may be higher, adding in costs for stormwater controls can offset the additional cost of using a porous system. The reason for this is that porous pavements can reduce the amount of curbs and gutters for a site as well as downstream collection and treatment facilities (Schueler, 1987). Figure 9 shows the cost comparisons between using conventional (dense) asphalt and a porous pavement. When factoring in off site stormwater controls, the porous site is the most cost effective (Ferguson, 2005).

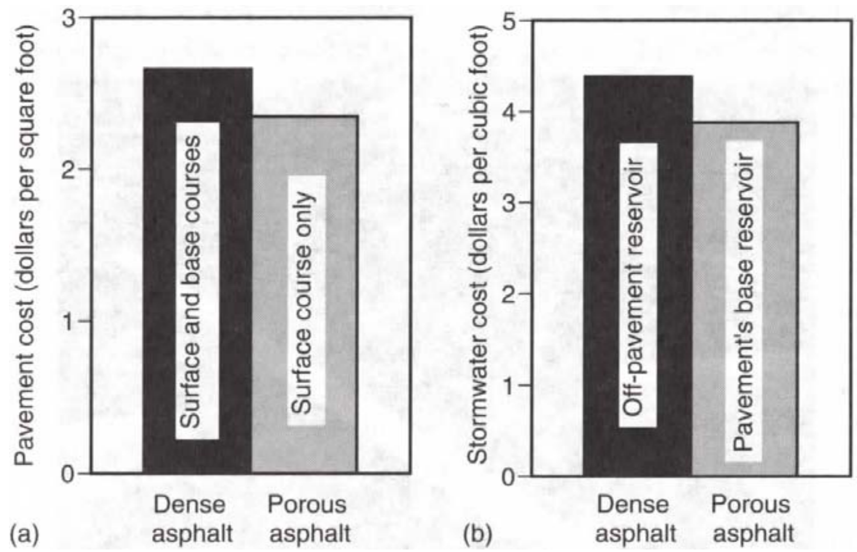


Figure 9: Cost Comparison for Dense Asphalt vs. Porous Asphalt (Ferguson, 2005). When factoring in all costs, porous pavements may be the most cost effective alternative.

Additionally, in a cost-benefit analysis for Netherlands highways, the Dutch Department of Public works showed that porous asphalt pavements were financially justifiable (van der Zwan, 1990). Additional costs from using porous asphalt were found in extra base course material and more frequent maintenance. However, savings were realized from increased traffic safety and decreased traffic congestion. The costs of additional deicing operations were not included in the analysis and no quantifiable benefit was associated with reduced rolling noise.

2.4.2. Requirements

In order for porous pavements to function properly, certain conditions are needed. High soil permeability, relatively flat grades on site, and low water tables and bedrock are all necessary for porous pavements to achieve the desired performance (Schueler, 1987). Good soil permeability is one of the most important conditions. Soils largely consisting of clays are not very pervious and will not allow water from a porous pavement to

infiltrate the soil and then recharge the groundwater (Boyer, 2005). Infiltration rates of at least 0.5 inches per hour are recommended for porous pavement applications (EPA, 1999). Flat grades help keep the water on the pavement long enough for it to infiltrate the porous surface. Low water tables are necessary so the soil directly below the pavement is not at risk of becoming saturated due to rising groundwater levels. High bedrock formations could also jeopardize the drainage of the site if the bedrock formed an impervious layer beneath the pavement.

2.4.3. Types

There are several types of porous pavements, including paving stones, structural turf, porous asphalt and porous concrete. Each has advantages and disadvantages, depending upon their intended use.

2.4.3.1 Paving Stones

UFC 3-120-10 defines block pavers, or paving stones, as manufactured paving blocks containing spaces where water can penetrate into the porous media placed underneath. Simply put, bricks or stones are arranged in a grid with space between each brick allowing water to flow to the soil beneath (Ciccocioppo, 2005). Traditionally, they are constructed on a crushed stone base (Smith, 2003). Figure 10 shows the cross-section of a typical paving stone system.

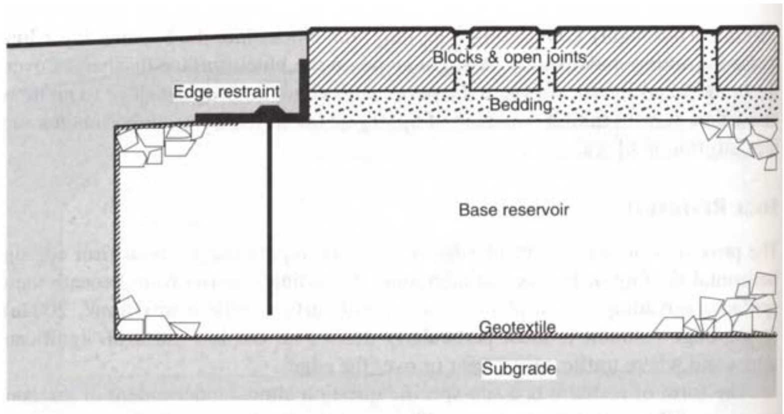


Figure 10: Typical Paving Stone Cross-section (Ferguson, 2005). Paving stones, or blocks, are separated by sections of pervious materials to allow for infiltration of water.

The increased infiltration between the stones and through the stone base can result in reduced runoff volumes and improved pollutant removal (UFC, 2004). The infiltration rates for paving stones can range from 10 to 20 inches of precipitation per hour (Smith, 2003) while conventional pavements offer near zero. Paving stones are thought to be fairly low maintenance due to the option of removing and replacing one faulty stone without affecting the remaining system (Ciccocioppo, 2005). However, paving stones have often been observed to settle unevenly, producing a poor driving surface (Ciccocioppo, 2005). Costs for various paving stones can be estimated from \$2 to \$4 per square foot (EPA, 2000). Although more expensive than porous asphalt or concrete, they do offer more unique design opportunities (Wilson, 2004).

Figure 11: Example Paving Stone Installation (Woodruff Block Company, 2005). Paving stone designs can add aesthetic value in addition to their functionality.

2.4.3.2 Structural Turf

Structural turf is a porous pavement type that can have the appearance of a grass field along with the structural integrity to support vehicular traffic. This pavement is often constructed of a plastic structure that forms a grid containing soil and grasses without impeding runoff infiltration (Figure 12). Many structural turf products offer 88-98% pervious area, closely replicating natural infiltration rates (Ferguson, 2005).

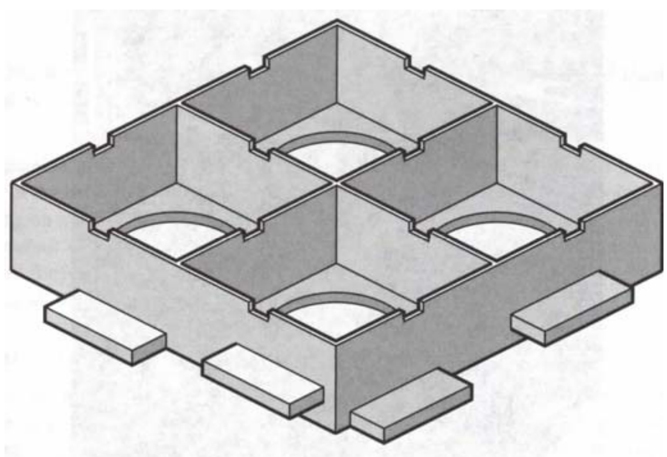


Figure 12: GeoBlock® Structural Turf Grid (Ferguson, 2005). The plastic grid offers structural support while the void spaces allow for grasses or gravels as fill.

Since these plastic structures are fairly flexible, they are easy to install and maintain, and are relatively unaffected by freeze-thaw and wetting cycles (Wilson, 2004). Another benefit from structural turf pavements is that they do not collect and store the sun's energy in the form of heat (Ciccocioppo, 2005). Therefore, utilizing these pavements will not contribute to the urban heat island effect and can help keep surrounding areas cooler.

Some maintenance concerns associated with structural turf are that they require regular watering and traditional mowing to keep the grass in good condition (UFC, 2004). Keeping the grass healthy is imperative in order to keep the soil portion of the pavement from being blown or washed away (Ciccocioppo, 2005). Heavy traffic or shadows from vehicles parked over the grass for extended lengths of time can also have negative impacts on grass health (Ciccocioppo, 2005). Costs range from $1 to $2 per square foot (Center for Watershed Protection, 1998). Figure 13 shows an installed system.

Figure 13: Netpave® 50 Application (Netlon, 2006). Plastic structure can be filled with grasses or gravels.

2.4.3.3 Porous Asphalt

UFC 3-120-10 defines permeable pavements as asphalt or concrete rendered porous by the aggregate structure. Simply stated, the fine aggregates normally found in asphalt or concrete are left out, allowing water to flow between the larger pieces of aggregate. These pavements still have "considerable strength and durability" without the fines found in conventional mixes (Ciccocioppo, 2005). Structurally, porous asphalt offers 73-79% of the strength of conventional asphalt (Heystraeten, 1990). Porous asphalt parking areas can also last longer than conventional asphalt due to the deeper base course offered by the reservoir structure (Wilson, 2004). Figure 14 shows an example of a porous asphalt system with various aggregate sizes in the reservoir structure. The choker course provides a smooth surface for the asphalt to rest on and the layer of smaller aggregate in the base reservoir helps to stabilize the reservoir structure.

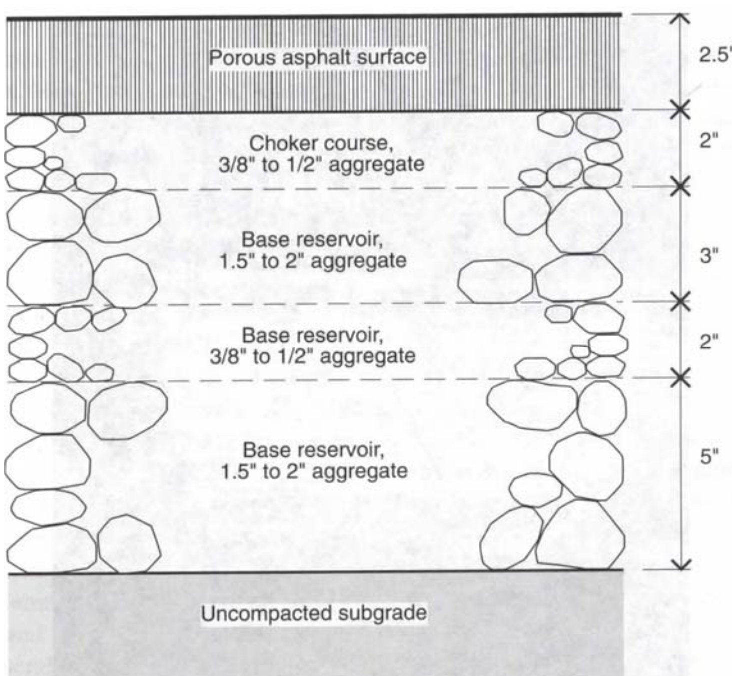


Figure 14: Example Porous Asphalt System (Ferguson, 2005). Porous asphalt over large aggregate stone offers very high permeability.

Porous asphalt can be patched with conventional impervious asphalt to fix potholes and cracks. However, impervious patches should not cover more than 10% of the pavement surface (Schueler, 1987). Porous asphalt parking areas (with all system components) are estimated to cost $2000 to $2500 per space which is 25% to 33% less expensive than porous concrete (Wilson, 2004).

Figure 15: Example Porous Pavement Application (Adams, 2003). Water pools on the conventional asphalt on the left, but is able to infiltrate the porous asphalt on the right.

2.4.3.4 Porous Concrete

Porous concrete is very similar in functionality and design when compared to porous asphalt. Again, the fines are removed from the mix leaving Portland cement (18-21% of the mix) and uniform sized aggregate to bind together (Wilson, 2004). The concrete is then laid over a gravel subbase, as shown in Figures 16 and 17 (Offenburg, 2005).

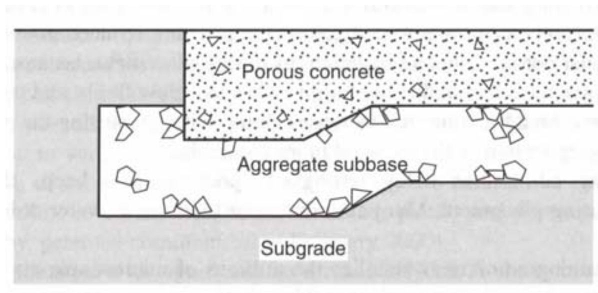


Figure 16: Typical Porous Concrete Structure (Ferguson, 2005). Porous concrete has a relatively simple structure with only an aggregate subbase and soil subgrade for support.

Figure 17: Cross-section of Porous Concrete (Offenburg, 2005). Porous concrete can be poured directly over a gravel base.

Installation of porous concrete requires a highly experienced crew in order to achieve the desired permeability. Maintaining proper water content and adhering to a limited working time places the greatest constraints on the crew (Wilson, 2004). Porous concrete can have compressive strengths ranging from 1000 to 4000 pounds per square inch (Offenburg, 2005). Today, porous concrete is most well known and most widely used in southern states (Wilson, 2004).

2.4.4. Advantages

There are several advantages associated with using porous paving alternatives. The following sections will describe five specific advantages.

2.4.4.1 Infiltration

In urban areas, up to 75% of the surface area is covered by roads and roofs, denying the majority of natural groundwater recharge (Wilson, 2004). By utilizing porous paving technology, much of this groundwater recharge could be regained. Booth and Leavitt (1999) conducted a field study in Renton, Washington, that showed two paving stone products and two structural turf products as being capable of 99% infiltration during precipitation events. Another experiment at the same site, four years later, recorded similar infiltration rates (Brattebo & Booth, 2003). A porous asphalt site in Willow Grove, PA, experienced 60-80% infiltration on their pavements (Schueler, 1987).

2.4.4.2 Water Quality

Urban stormwater has been shown to contain high levels of pollutants, heavy metals, and suspended solids. Porous pavements have the ability to intercept many of these pollutants before they can reach our groundwater systems by acting as a filter medium (Stotz, 1994). Particles which get caught in the pavement structure often carry the majority of pollutants found in urban runoff, especially heavy metals (Colandini, 1995). These particles are usually sand or dirt and enter the structure with runoff water but get stuck in the structure's aggregate or filter layers. Porous pavements have also been shown to effectively breakdown hydrocarbons through microbial processes (Coupe, 2003). Microorganisms live within the pavement's structure and feed off of oil contaminants, naturally biodegrading them.

In a study near Rezé, France, infiltrated water from porous pavements was shown to have reduced suspended solids levels (64% less) and lead contents (79% less) when compared against runoff collected from a conventional stormwater collection system

(Legret, 1996). The study found that other heavy metals (lead, copper, cadmium, and zinc) were mainly caught in the pervious asphalt layer and on the geotextile membrane below the reservoir structure. After the four year study, the soil below the pervious asphalt structure was not significantly contaminated. The above findings were confirmed through a follow up experiment on the same site after the porous pavement had been in use for a total of eight years of operation (Legret, 1999). Another porous pavement site in Nantes, France, showed similar particulate retention and water filtration capabilities as shown in Figure 18 (Pagotto, 2000).

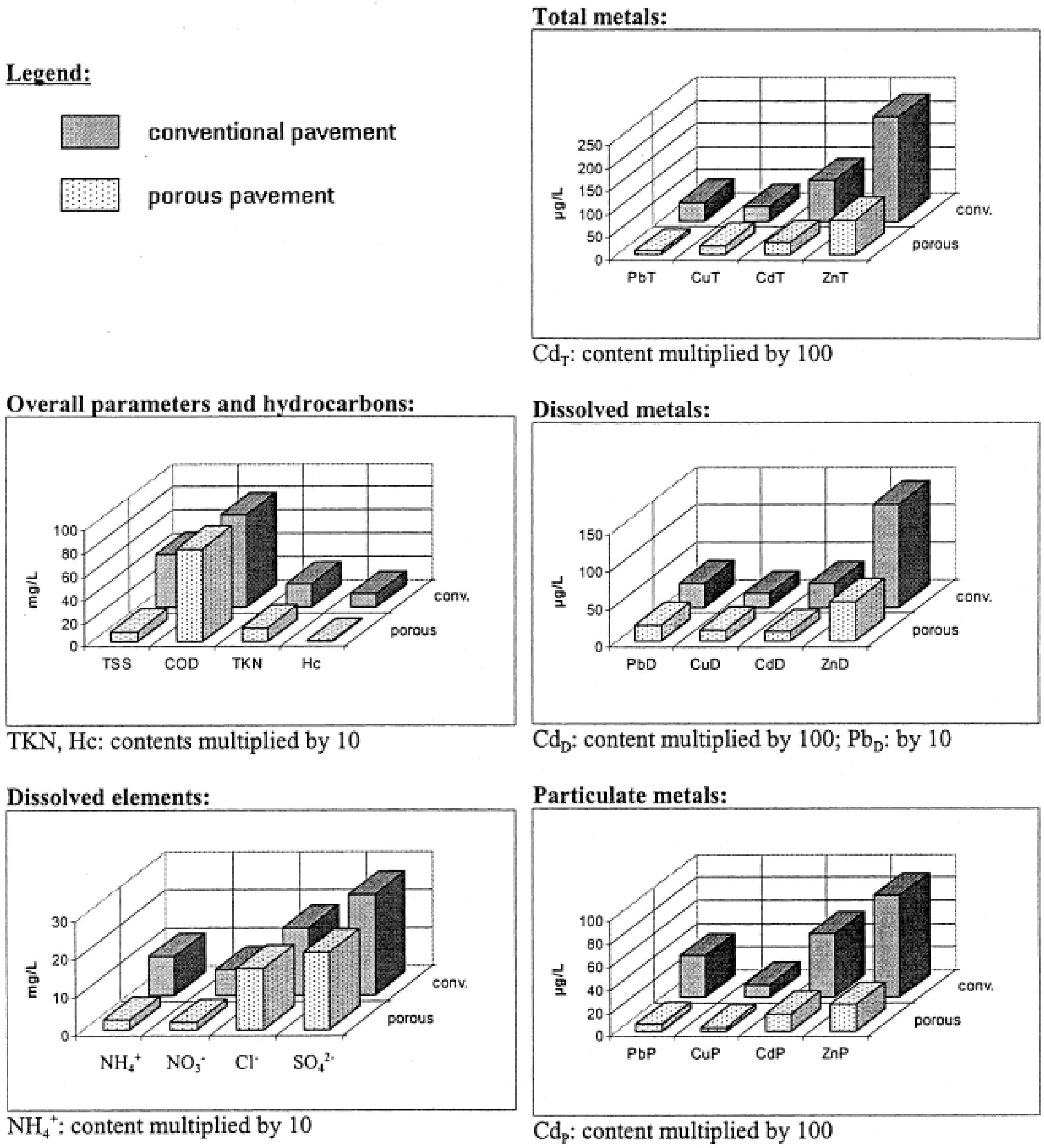


Figure 18: Conventional vs. Porous Pavement Runoff Pollutants (Pagotto, 2000). Porous pavements performed significantly better at removing metals and particulates from runoff waters.

Several scientists have expressed their concern about allowing pollutants to collect in the soil, fearing that they would eventually infiltrate drinking water supplies (Shaver, 1986 and Delolme, 2004). Legret (1999) used a mathematical model, LEACHM, to simulate the movement of heavy metals through the soil. The results of the model

showed a low threat from metals trapped in the soil because all concentration levels were below regulation levels. Cadmium did show a 30 cm migration but was not thought to be a great threat to groundwater because its concentration was very low. Delolme (2004) produced a model that showed maximum zinc concentrations released into a sandy medium and estimated the time it would take to travel through that medium. However, he felt that the model did not effectively encompass all relevant chemical processes and that more research needed to be done if these areas before a more accurate model would be possible.

In another study in France (Colandini, 1995), the amount of heavy metal contamination was directly linked to the amount of road traffic over that section of pavement. The study also found that porous pavements were effective at removing heavy metals from potential stormwater. This was mainly as a result of heavy metals collecting on sand particles and being caught in the pavement structure (Colandini, 1995).

Porous pavements are also effective at intercepting and degrading hydrocarbons. Oil based pollutants, mainly from automobiles, often collect on pavement surfaces until they are washed off by precipitation events. Typically, these pollutants are carried by stormwater runoff to treatment facilities or directly into natural waterways. However, studies have shown porous pavements to be 98.7% effective at trapping hydrocarbons and also very effective at biodegrading trapped oil (Coupe, 2003). Coupe (2003) demonstrated that increasing the microbial population within a porous pavement would degrade more oil but he was not able to maintain the population after the initial inoculation.

2.4.4.3 Sound Absorption

The majority of noise on highways is the result of contact of tires rolling on the road surface. This "rolling noise" is caused by an air-pumping phenomenon in which air is compressed between the tire treads and the road surface. The increased number of cavities in porous pavements helps avoid this air compression thus reducing rolling noise (Camomilla, 1990). Conventional road surfaces tend to reflect sound energy and porous road surfaces tend to absorb that energy (Golebiewski, 2003).

Heystraeten (1990) noted that rolling noise was attenuated both inside and outside of vehicles on porous asphalt rather than conventional pavements due to a higher sound absorption coefficient. According to his estimates, overlaying grooved concrete expressways with porous asphalt may reduce noise by 6 to 10 dB(A) (Heystraeten, 1990). Fujiwara (2005) found porous asphalt to reduce noise by 5 to 6 dB, slightly lower than Heystraeten's (1990) estimates. In an experiment by Golebiewski (2003) in Poland, sound levels were recorded as vehicles traveled over sections of conventional, dense asphalt and over porous asphalt. Figure 19 shows that porous pavement offered reduced sound exposure levels for all speeds tested. Golebiewski (2003) directly linked the sound exposure level with a subjective assessment of annoyance. Since porous pavements produced lower sound levels, they were found to be less annoying.

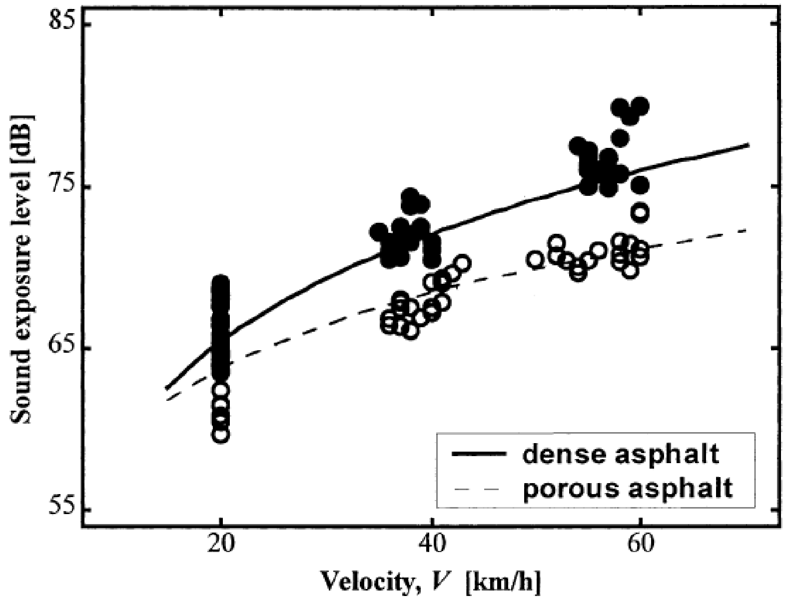


Figure 19: Sound Exposure Levels vs. Vehicle Speed (Golebiewski, 2003). Porous pavements offered lower sound levels overall.

2.4.4.4 Safety

Aside from benefits of improved stormwater quality and quantity, porous pavements offer significant safety benefits for highway drivers, especially in inclement weather. Porous asphalt highways in Switzerland have been shown to have better skid resistance at higher vehicular speeds than conventional asphalt highways (Isenring, 1990). They have also been shown to be effective at reducing ponding on the road surface through infiltration. This reduction of ponding decreased the likelihood of hydroplaning when compared to conventional asphalt paving. Porous asphalt was also shown to significantly reduce the “splash and spray” effect behind moving vehicles. Reflections on wet road surfaces are also reduced, allowing for more visible road markings and less headlight glare on rainy evenings (Schueler, 1984; Heystraeten, 1990). The elimination of hydroplaning and the increased visibility for drivers makes porous

pavements a safer driving surface during precipitation events by reducing the potential of accidents (Stotz, 1994).

2.4.4.5 Reduced Heating

Structural turf offers the most significant reduction in the urban heat island effect. Transpiration in the turf layer of the pavement cools the adjacent atmosphere rather than heating up like an asphalt or concrete surface (Wilson, 2004). The permeable nature of porous pavements does not only allow for the flow of water but also for air. This movement of air through the pavement and underlying soil helps promote healthy trees by increased soil aeration (Ferguson, 2005). The presence of long-lived, healthy trees help shade paved areas, keeping them cooler (Wilson, 2004).

2.4.5. Disadvantages

There are some disadvantages to using porous pavements. First, and often most noted, is the issue of initial cost. As discussed earlier, porous systems appear more costly until curbing and stormwater drainage fixture costs are added in. Another major issue is durability. One study identified 5 possible risks associated with the installation of a porous pavement. Those risks were: clogging, poor permeability of the draining liner, poor compacity of pavement layers, longitudinal slope fault, and geotextile deterioration (Alfakih, 1995). According to Boyer, most porous pavement failures occur when soil types are not considered, maintenance is not carried out properly, or regional weather is not factored in (Boyer, 2005). When soil types are not considered, low soil permeability can negate the purpose of the pavement by not allowing the water to percolate through

the soil. If maintenance is not carried out regularly, the porous surface of the pavement can become clogged with sand and dirt particles, reducing the permeability of the pavement. When regional weather is not considered, the pavement may crack or heave during freeze/thaw cycles due to insufficient depth in the reservoir structure. This section will focus on clogging and winter performance.

2.4.5.1. Clogging

Premature clogging is a significant drawback for porous pavements (Schueler, 1987). In order to reduce the risk of premature clogging, porous pavements should not be used in areas where the road surface will receive large amount of dust, dirt, or other foreign debris. For example, farm roads may frequently experience muddy tires that could quickly clog the pores with mud, reducing the permeability of the pavement. Higher traffic areas are preferred for porous asphalt applications due to the self-cleaning effect that constant vehicle traffic has on the road surface (Heystraeten, 1990). However, Ruiz (1990) stated that heavy traffic volumes cause faster clogging than lighter volumes and Colandini (1995) showed that heavier volumes cause higher concentrations of heavy metals. In order to maintain designed permeability, maintenance cleanings with a vacuum sweeper should be accomplished four times per year (Shaver, 1986). However, since clogging particles may be contaminated by heavy metals, they may need to be treated as toxic once removed from the pavement (Colandini, 1995). Clogged sections of porous pavements may be remediated through vacuum sweeping and, in more serious cases, by drilling half-inch holes at regular intervals throughout the problem areas (Schueler, 1987).

2.4.5.2. Winter Performance

Porous pavements are more common in areas that do not experience winter frosts because freezing conditions have the potential to damage the pavement structure (Boyer, 2005). In areas of deep frost penetration, extending the base course below the maximum frost depth is one method to help minimize the risk of frost heave (EPA, 2002). Also, snow and ice maintenance is more difficult to accomplish through the traditional methods of sanding and salting. Sand can clog the pores in the pavement surface and large amounts of salt may have negative impacts on the quality of the local groundwater (Ciccocioppo, 2005).

Past studies have shown that porous pavements cooled faster (due to high porosity and surface area), allowed snow to attach faster, and allowed ice to form faster (Camomilla, 1990). There is also a noted decrease in the effectiveness of traditional salt solutions. Porous pavements may require double the normal amount of salt to help keep roads clear of snow and ice before snowfall (Ruiz, 1990). These surfaces should also be plowed shortly after snowfall to reduce snowfall penetration into lower levels of the pavement. However, plowing can also compress snow into pores and cause sporadic melting, creating a semi-liquid slush that freezes easily (Camomilla, 1990). In order to avoid causing damage to the pavement surface, the plow should slightly elevated above the pavement or a rubber edge may be used. Other researchers state that ice formation on porous versus nonporous pavements may occur at different rates on each surface depending on conditions but neither is universally safer than the other in terms of winter skid resistance (Heystraeten, 1990).

2.5. Value-Focused Thinking

The practice of decision analysis can be described as a five step process: pre-analysis, structural analysis, uncertainty analysis, value analysis, and optimization analysis (Keeney, 1993). Decision analysis attempts to provide tools to help a decision-maker use known information about a problem, factor in uncertainties in the possible outcomes, and consider his/her own values before selecting the best decision for his/her situation. The purpose of this section is to introduce and describe one decision analysis tool called Value-Focused Thinking (VFT). VFT is a strategic, quantitative approach to decision-making that uses specified objectives, evaluation measures, and value hierarchies (Kirkwood, 1997). Keeney (1992) describes VFT in more basic terms as "first deciding what you want and then figuring out how to get it."

2.5.1. Concepts and Components

Before describing VFT more thoroughly, this section will begin with a brief description of some decision theory basics. A decision can be defined as the choice between several alternatives with "differing consequences or outcomes" (Kirkwood, 1997). Most decisions are difficult because only one alternative can be selected and the outcome associated with each alternative often has some degree of uncertainty associated with it (Kirkwood, 1997). For this reason, a structured approach should be used to assist the decision-maker to view the decision objectively and strategically.

Strategic decision making can be accomplished by using a structured decision making process that quantitatively describes all elements of the decision. This quantification of decision elements is important in that it makes the decision-maker be

very specific in his/her reasoning (Kirkwood, 1997). A five step approach to making strategic decisions was proposed in *Strategic Decision Making*: specify objectives and scales, develop alternatives, determine the effectiveness of each alternative, consider tradeoffs among objectives, and select the best alternative (Kirkwood, 1997).

An objective is a goal that the decision-maker wants to achieve. The three characteristics of an objective are a decision context, an object, and a direction of preference (Keeney, 1992). There are two main types of objectives: fundamental objectives and means objectives. Fundamental objectives are directly tied to the decision situation while means objectives merely impact the degree in which another fundamental objective can be achieved (Keeney, 1992). Figure 20 offers an example showing the difference between fundamental objectives and means objectives.

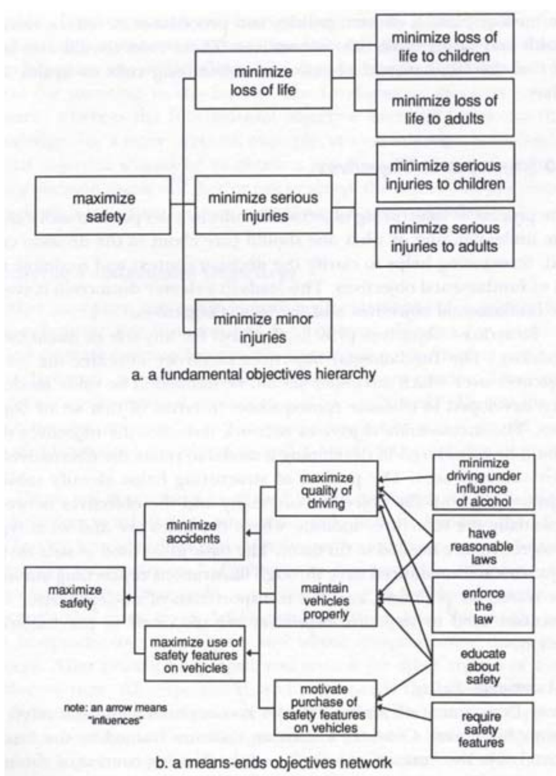


Figure 20: Fundamental Objectives and Means Objectives Example (Keeney, 1992). Focusing on fundamental objectives is important because they are tied directly to the decision situation.

Most decision problems begin with the presence of at least two alternatives (Keeney, 1992). From there, the decision problem then focuses on choosing between those alternatives based on the means objectives. The approach described above is also known as Alternative-Focused Thinking (AFT). AFT follows the sequence of five activities shown in Table 1. After a problem is recognized, the decision-maker then looks for what alternatives are available. Once the alternatives are identified, then the decision-maker's values are considered. Keeney (1992) defines values as what the decision-maker feels to be important. These values are then used to evaluate each alternative before selecting the best one.

Table 1: Alternative-Focused Thinking Activities (Keeney, 1992). Five main activities comprise Alternative-Focused Thinking.

AFT Sequence of Activities
1) Recognize a Decision Problem
2) Identify Alternatives
3) Specify Values
4) Evaluate Alternatives
5) Select an Alternative

Keeney feels that the AFT process is "too narrow" and "reactive" because all possible alternatives are not identified and the objectives are often means objectives rather than fundamental objectives. VFT differs from AFT in the sequence of activities in the decision-making process. Steps 2 and 3 (Identify alternatives and specify values) in Table 1 are reversed so that specifying values comes before the identification of alternatives. Table 2 demonstrates the VFT sequence of activities. By looking at values first, the decision-maker can take a "proactive" stance by focusing on his fundamental objectives and then creating a broader range of alternatives by avoiding anchoring to any

previously identified alternatives (Keeney, 1992). The last two steps of evaluating and selecting alternatives are the same for both AFT and VFT.

Table 2: Value-Focused Thinking Activities (Keeney, 1992). VFT differs from AFT in that the second and third steps are reversed.

VFT Sequence of Activities
1) Recognize a Decision Problem
2) Specify Values
3) Create Alternatives
4) Evaluate Alternatives
5) Select an Alternative

2.5.2. VFT 10 Step Decision Making Process

Shoviak (2001) created a 10 step decision-making process based on VFT concepts. This thesis will use Shoviak's process. Figure 21 demonstrates Shoviak's process in a flow chart format. This section will briefly describe steps one through five. Chapter 3 (Methodology) will then use those steps (one through five) and step six (alternative generation) to create the pavement selection model. Chapters 4 and 5 (Analysis and Recommendations) will then describe and apply the remaining steps to evaluate the pavement types described earlier in this chapter.

In step one, the problem is identified. As simple as this step sounds, it is often not done properly. Before any further steps can be accomplished, a clear, concise problem statement is needed so efforts are not wasted pursuing a tangent that is only related to the real problem. In this stage, one must be careful to identify the problem itself and not just a symptom of that problem.

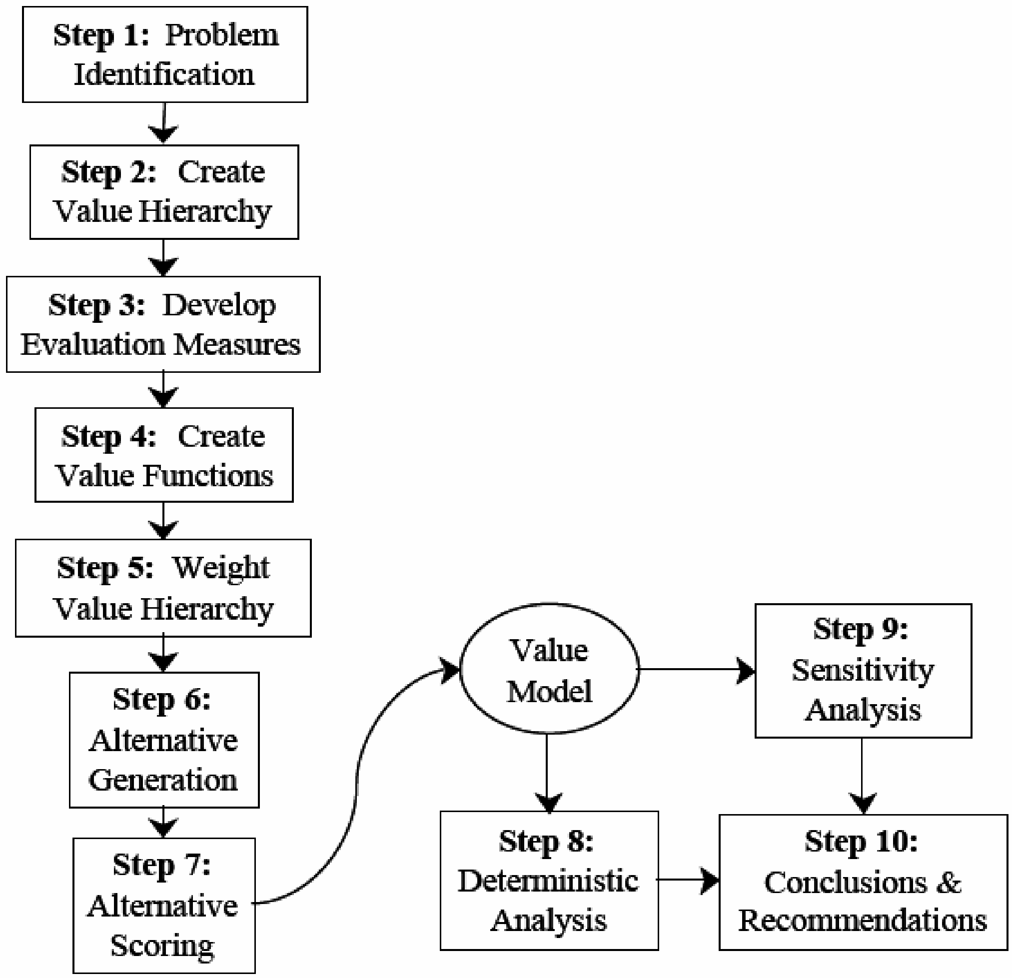


Figure 21: VFT 10 Step Process (Shoviak, 2001)

Creating a value hierarchy is the second step in the process. Kirkwood (1997) defines a value hierarchy as a “hierarchal or treelike structure” that “encompasses the entire set of evaluation considerations, objectives, and evaluation measures for a particular decision analysis.” Evaluation considerations can be any area of concern related to the decision at hand. Objectives are what the decision-maker wants to achieve (Keeney, 1992) with respect to the evaluation considerations (Kirkwood, 1997). Evaluation measures describe the “degree of attainment” of which an objective is satisfied (Kirkwood, 1997).

The hierarchal structure is composed of tiers and branches. Tiers, or layers, are made up of evaluation considerations that are the same distance away from the top of the hierarchy (Kirkwood, 1997). The closer an evaluation consideration is to the top of the hierarchy, the more important it is. Branches are composed of all the objectives and evaluation measures that stem from a single evaluation consideration or fundamental objective. Figure 22 shows a generic value hierarchy with the associated tiers and branches.

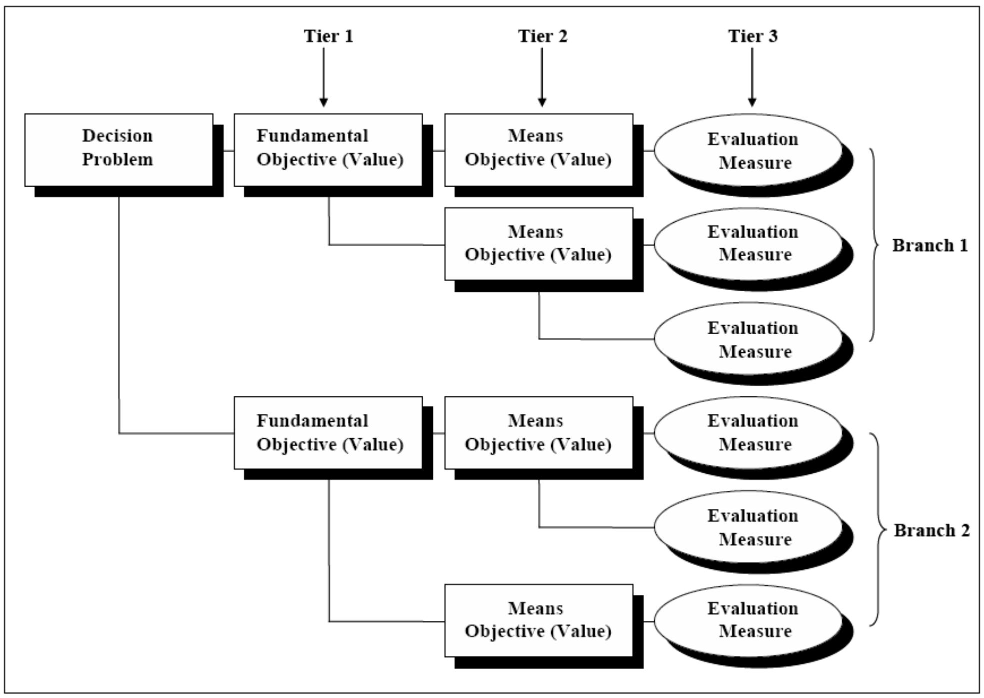


Figure 22: Generic Value Hierarchy (Jeoun, 2005). A value hierarchy is composed of tiers and branches that support the fundamental objectives of the problem.

The third step is to develop evaluation measures to determine the “degree of attainment of the objectives.” (Kirkwood, 1997) Evaluation measures can be categorized under a natural or constructed scale and also under a direct or proxy scale (Kirkwood, 1997). A natural scale is any scale that is known and understood by everyone while a constructed scale is used when no natural scale exists and a new scale must be created as

a means of measurement. A direct scale is able to “directly measure the level of attainment of an objective” and a proxy scale indicates how well an objective is being achieved but doesn’t make a direct measurement (Kirkwood, 1997).

The next step is to create a Single Dimension Value Function (SDVF). A SDVF is a method of converting evaluation measures into a standardized, unitless scale from zero (least preferred) to one (most preferred). Since each evaluation measure has a different unit of measurement, a conversion is necessary to effectively compare the measures on the same scale. Discrete SDVFs have a set value for each possible score, while continuous SDVFs have a continuous range of values for any possibility. Two types of continuous SDVFs are piecewise linear and exponential. A piecewise linear SDVF places specific relative value increments for each possible score of the evaluation measure (Kirkwood, 1997). An exponential SDVF uses a mathematical formula to represent a continuous range of value increments for all possible evaluation measure scores. Figure 23 compares generic piecewise linear and exponential SDVFs graphically.

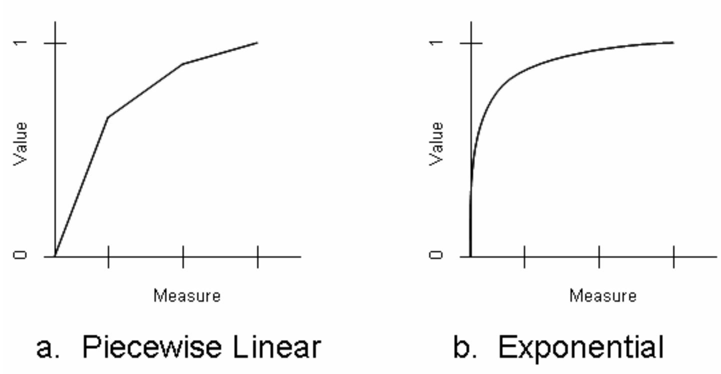


Figure 23: Generic Piecewise Linear and Exponential SDVFs. Different evaluation measures may have discrete or continuous value functions associated with them.

Following the creation of an appropriate SDVF, the fifth step is to weight the value hierarchy. The purpose behind weighting the value hierarchy is to identify which

evaluation measures are most important to the decision-maker. The change in value an alternative receives by moving a measure's score from its least preferred level to its most preferred level is the measure's weight (Kirkwood, 1997). Weightings are typically assigned in two different ways: globally or locally. Global weightings ensure that the weights for each measure on the lowest tier sum to one. The weights for the next tier in the hierarchy are determined by summing the weights of the measures below it. Local weighting begins at the top tier of the hierarchy rather than the lowest. Once the top tier is weighted so that the sum of the weights is equal to one, each branch is then weighted in the same manner. The weights within each branch, the local weights, are then multiplied by the weight of the higher objective to attain the global weights (Jeoun, 2005).

2.5.3. VFT Advantages

VFT has several advantages as a decision-making tool. When faced with a decision problem, it first allows the user the ability to focus his/her efforts on gathering the right information for the problem according to what was identified as being important. The VFT process is also helpful in designing the proper alternatives in situations where pre-determined alternatives are not readily available. By using VFT, all the important considerations are laid out for all involved to factor in when creating alternatives. This is especially important when the decision problem is large enough to have many stakeholders involved in the outcome. Maintaining clear communications about the objectives will help keep all stakeholders informed and eventually make the ultimate choice of alternatives easier (Kirkwood, 1997).

2.6. Summary

Following Low Impact Development principles and utilizing Best Management Practices is a good way for communities to stop adding to the problem of stormwater runoff. Porous pavements can help by reducing runoff volumes and improving water quality for urban areas and their watersheds. Porous pavements have been shown to offer numerous environmental benefits, driver safety improvements, and to be an effective substitute for conventional methods.

Value-Focused Thinking offers a systematic, quantitative approach to decision-making. By avoiding the traditional approach of only considering values after alternatives are identified, all feasible alternatives can be recognized and considered, rather than just the ones that are readily available. By utilizing Value-Focused Thinking, a decision-maker choosing a pavement system can take a proactive, strategic approach to decision problems, ensuring proper attention is paid to those objectives that are truly important.

3. Methodology

3.1. Overview

This chapter will describe the methodologies used to examine the five research questions set forth in Chapter 1. Table 3 summarizes these research questions and identifies the methodology used to address them. The first three questions were researched through a thorough review of current literature and studies. These questions were answered and discussed in the Literature Review section of this document (Chapter 2). The two remaining questions relate to the formulation of a decision model to help military decision-makers consider various pavement options, including porous pavements, before making a selection. These two questions will be answered in detail throughout the sections of this chapter.

Table 3: Summary of Research Questions. This table reviews the research questions and specifies their location in this document.

	Research Question	Methodology	Chapter
1	What are the characteristics, benefits, and disadvantages associated with different types of porous pavements?	Literature Review	2
2	Where have porous pavements been used successfully in the past?	Literature Review, Case Study	2
3	What are the environmental and economic impacts of stormwater discharges from urban areas?	Literature Review	2
4	What is the appropriate methodology for choosing to construct a parking lot from a porous pavement rather than a conventional pavement?	Value-Focused Thinking	2, 3
5	What is important to Air Force decision-makers when selecting paving options?	Value-Focused Thinking	3

This chapter will discuss the first six steps in the 10 Step Value-Focused Thinking (VFT) Process: identify the problem, create a value hierarchy, develop evaluation measures, create value functions, weight the hierarchy, and generate viable alternatives as the solution to the problem (Shoviak, 2001). The last four steps will be accomplished in the analysis and recommendation sections of this thesis (Chapters 4 & 5).

3.2. Step One: Problem Identification

The Air Force Center for Environmental Excellence (AFCEE) expressed interest in the use of porous pavements on military installations to help control the quantity and quality of base stormwater runoff. Although porous pavements have been shown to provide many benefits, their higher installation costs and maintenance issues often keeps them from being considered as a viable option. Additionally, there is no decision analysis method on how to select a porous pavement for a particular installation.

As a first step towards the consideration of porous paving technology, this thesis will focus solely on pavement selection for parking lots. Today's Air Force parking lot pavement selection methodology is relatively simple: heavy-duty vehicle/aviation maintenance areas are concrete, all others are asphalt. Since there is no methodology to consider other paving possibilities for parking areas, this thesis will attempt to determine when and where porous pavements should be chosen over conventional methods. Therefore, the driving question of this model will be: What is the best pavement option for a newly constructed parking lot?

3.3. Step Two: Create Value Hierarchy

Before attempting to build the hierarchy for the problem of pavement selection, a decision-maker first had to be identified. Instructors from the Air Force Institute of Technology's Civil Engineer and Services School were appropriate candidates due to their position as educators of Air Force civil engineers. A team consisting of three instructors (two pavements course directors and one environmental course director) was created to collectively represent the decision-maker in this VFT model.

As described in Chapter 2, a value hierarchy is a "treelike structure" that "encompasses the entire set of evaluation considerations, objectives, and evaluation measures" a decision-maker uses to analyze a decision (Kirkwood, 1997). During a tabletop discussion, the process of building a hierarchy began with the solicitation of values (issues of importance) from the decision-maker. This was accomplished by asking the decision-maker what issues were important when choosing a pavement for a parking area. All responses were then recorded on index cards and laid out on the table. After all possible values had been identified; the index cards were grouped into piles of similar values. Broad values were broken down into more narrow values, duplicates were eliminated and then the remaining values were categorized. Initially, all values were grouped into four categories of means objectives: *Cost*, *Contract Concerns*, *Manpower Impact*, and *Environmental Impacts*. As you may recall from Chapter 2, fundamental objectives are directly tied to the decision situation while means objectives merely impact the degree in which another fundamental objective can be achieved (Keeney, 1992). These means objectives fell under three overarching fundamental objectives. The

fundamental objectives were *Resources, Operations,* and *Environment*. These fundamental objectives are shown in Figure 24.

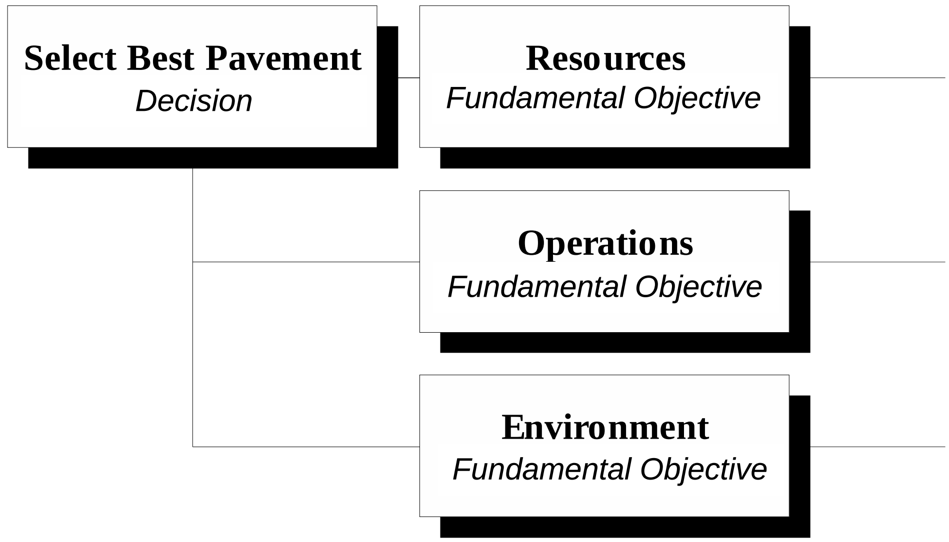


Figure 24: Pavement Selection Value Hierarchy. Three fundamental objectives were identified: *Resources, Operations,* and *Environment*.

3.3.1. *Resources*

The purpose of the fundamental objective of *Resources* is to quantify all financial costs and problems with the paving contract for the end user (the base civil engineer). *Costs* can be in the form of the initial installation cost of the system, the annual maintenance costs, and costs associated with any additional equipment necessary to maintain a certain system (i.e. a vacuum sweeper for a porous concrete or porous asphalt pavement). It is important to note that the initial installation costs include additional design and material costs necessary to 'beef up' a system in order to function properly under regional climate and soil conditions. Cost avoidance is also considered through *Contract Concerns*. Costs incurred due to rework by inexperienced contractors and lengthy construction times are two portions of the *Contract Concern* objective. Figure 25 shows the fundamental objective of *Resources* and its associated means objectives.

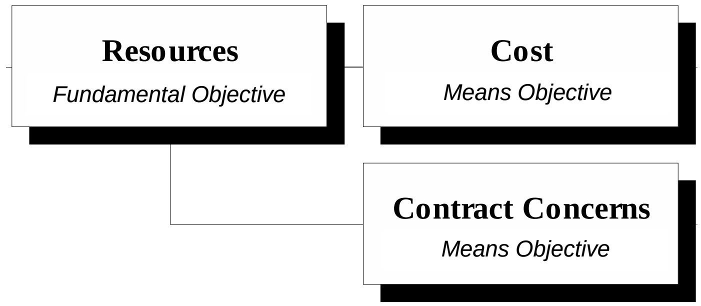


Figure 25: *Resources* Fundamental Objective. *Cost* and *Contract Concerns* are the two means objectives under the fundamental objective of *Resources*.

3.3.2. *Operations*

The purpose of the fundamental objective of *Operations* is to identify key considerations in how the pavement system will perform under certain conditions. *Manpower Impacts* captures the effect the system will have on base civil engineers in terms of man-hours dedicated to oversight, maintenance, and training as well as the operational burden of pavement replacement. Figure 26 shows the fundamental objective of *Operations* and its associated means objective.

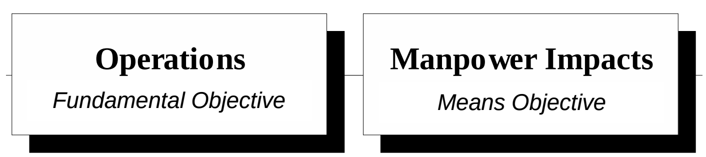


Figure 26: *Operations* Fundamental Objective. *Manpower Impacts* is the means objective under the fundamental objective of *Operations*.

3.3.3. *Environment*

The purpose of the fundamental objective of *Environment* is to recognize the value in acquiring a system that not only performs well as a paved surface but also minimizes adverse environmental impacts caused by its presence. As discussed in Chapters 1 & 2, anytime a pavement replaces a natural area, the natural hydrologic cycle is affected. The

degree to which that cycle is affected can be a function of how pervious the paving system is. Figure 27 shows the fundamental objective of *Environment* and its associated means objective.

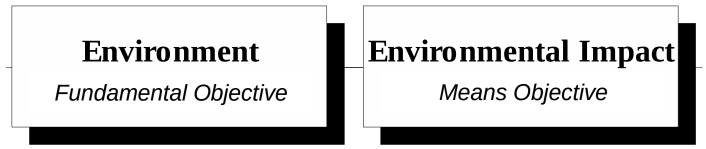


Figure 27: *Environment* Fundamental Objective. *Environmental Impact* is the means objective under the fundamental objective of *Environment*.

3.4. Step Three: Develop Evaluation Measures

The third step in Shoviak's VFT process is to create evaluation measures. Simply put, an evaluation measure tells a decision-maker how well they have met the values set forth by their means objectives. This section will detail the manner in which these values will be quantified and evaluated. The value hierarchy in Figure 28 shows the values that will be evaluated under this model.

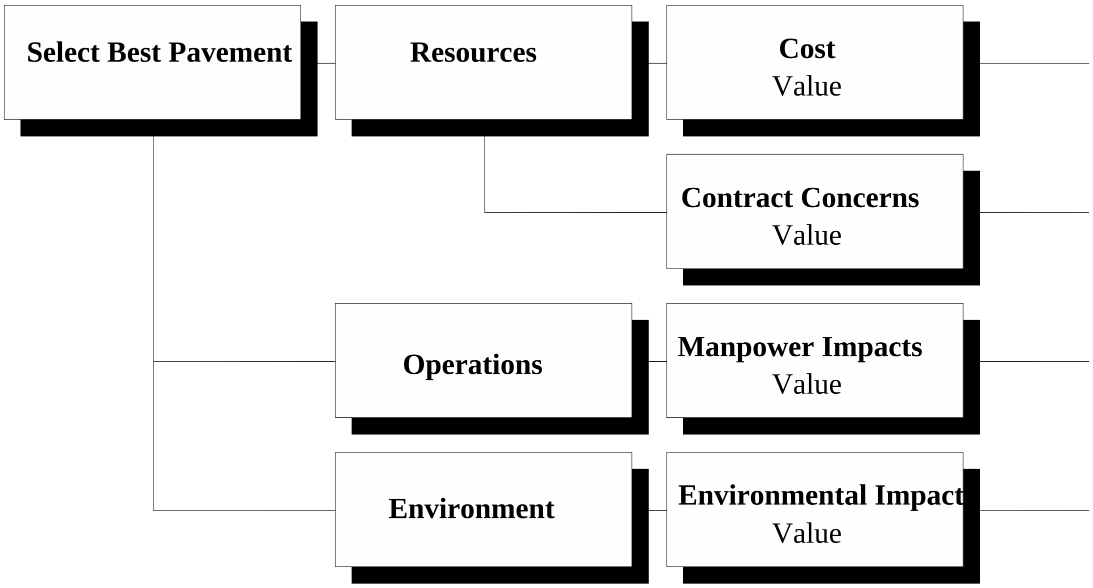


Figure 28: Pavement Selection Value Hierarchy. Four main values will be evaluated in this model.

3.4.1. *Cost*

Three evaluation measures were specified to evaluate the means objective of *Cost*. The decision-maker felt that *Cost* could be described as the categories of installation, maintenance and additional equipment costs (as shown in Figure 29). Installation Costs were defined to be any expenses, both material and labor, necessary to install a new pavement and make that paving system operational, including design and material additions for regional conditions. In areas with a high number of freeze/thaw cycles, significant design changes may be necessary to prevent the pavement from experiencing frost heave. These design changes will be added to normal installation costs. A fully-operational system was also thought to include all amenities necessary to transport stormwater into the existing base infrastructure or to collect and treat on site. Maintenance Costs exist in typical surface repairs (joint sealing, cracking, and spall repair) as well as periodic resurfacing (overlays), and the replacement of the system at the end of its life cycle. Additional Equipment Costs assesses additional expenses that may be necessary if the base civil engineers do not have a vacuum sweeper in their inventory. All costs will be evaluated in current year dollars.

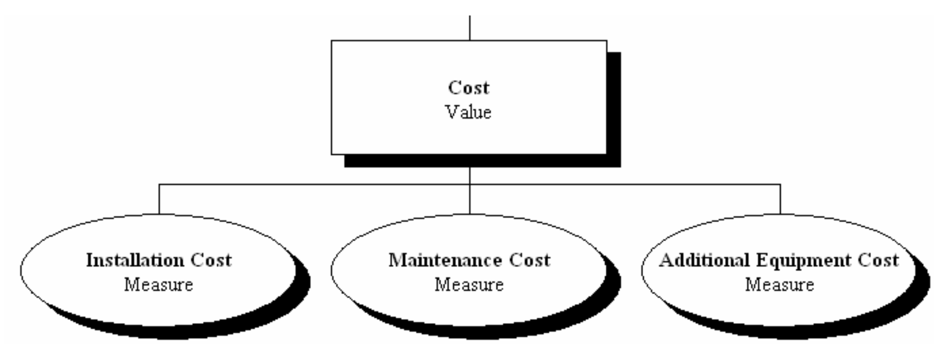


Figure 29: Evaluation Measures for *Cost*. *Cost* is measured by expenses from pavement installation, life cycle maintenance, and the purchase of additional necessary equipment.

3.4.2. *Contract Concerns*

The decision-maker identified two main areas under *Contract Concerns* that should be recognized in the value model. The first concern was the issue of how much experience local contractors had with various paving systems. At most locations, it was assumed that contractors installing traditional paving systems (asphalt and concrete) would have more experience (defined as the number of successful installations) than contractors installing porous paving systems. The measure of Contractor Experience will ensure that the model recognizes contractors with enough experience to offer the best chance at a successful installation. Another concern was how long a particular system would take to install from start to finish. The decision-maker believes that the shorter this Construction Time is in duration, the more value it offers to base engineers. Figure 30 shows the value of *Contract Concerns* and its associated measures.

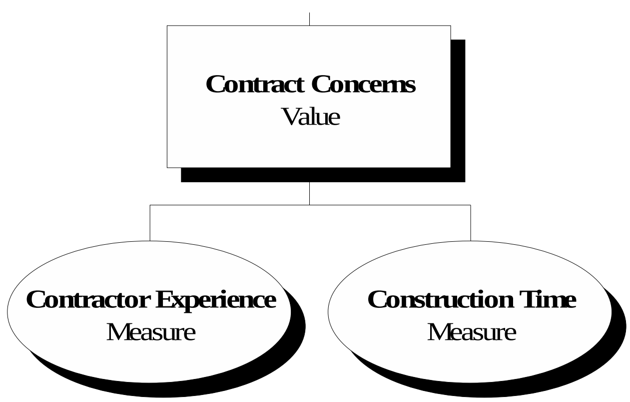


Figure 30: Evaluation Measures for *Contract Concerns*. *Contract Concerns* is measured by Contractor Experience and Construction Time.

3.4.3. *Manpower Impact*

Manpower Impact was described as the effect a paving system would have on base engineering resources, particularly manpower. Since Quality Assurance Evaluation

(QAE) inspectors are required to be present at key phases of traditional pavement installations, the decision-maker was concerned that more complicated systems (i.e. porous concrete) would require more oversight. The Inspection Man-hours measure captures this concern. Any additional man-hours above the status quo for traditional methods were viewed as a negative feature for pavement alternatives. The second measure, Sweeping Man-hours, assesses the impact a sweeping requirement has on additional man-hours that need to be diverted to the maintenance of the pavement system. The awareness of maintenance needs for porous pavements would also need to be taught through some degree of technical training. Training Man-Hours captures this requirement. Lastly, Life Span Durability was intended to capture the inherent value in installing a pavement with a longer life span. A pavement with a longer life span is superior to one of shorter length because of the logistical issues associated with closing a parking lot and sending vehicles elsewhere while installing a new system. The four measures of *Manpower Impacts* are shown in Figure 31.

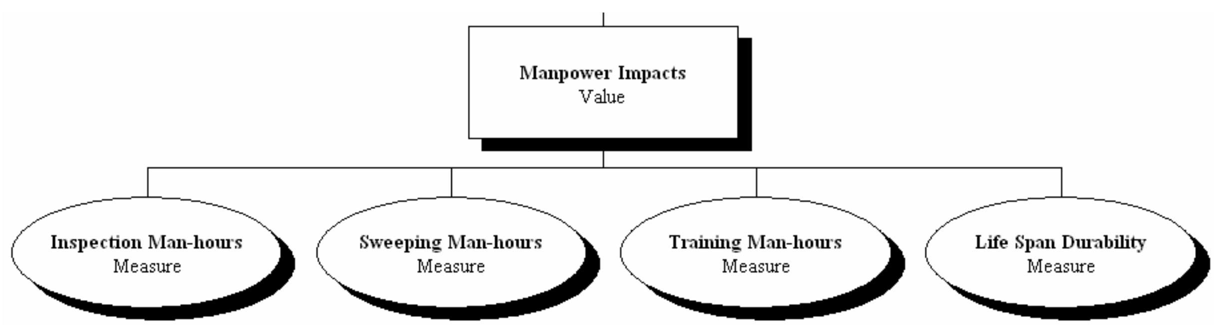


Figure 31: Evaluation Measures for *Manpower Impacts*. *Manpower Impacts* is measured through man-hours dedicated to oversight, maintenance, and training as well as the operational burden of pavement replacement.

3.4.4. *Environmental Impacts*

Although typically not at the forefront of a base engineer's criteria for selecting a pavement, the decision-maker determined several important measures to help identify the *Environmental Impact* associated with the installation of a parking lot. When a new pavement is installed, it has the potential to block the natural infiltration of precipitation for the area under the pavement surface. The measures of Degree of Perviousness and Pollutant Removal Capability attempt to evaluate the value potential associated with avoiding the expansion of downstream stormwater treatment facilities by allowing parking lot stormwater to be infiltrated and treated on site. Of even greater importance to the decision-maker was whether or not the selection of a porous pavement would contribute to practices identified in the base's Stormwater Pollution Prevention Plan (SWPPP). This measure provides the greatest incentive for a base to consider a porous paving system. The measures associated with *Environmental Impact* are shown in Figure 32.

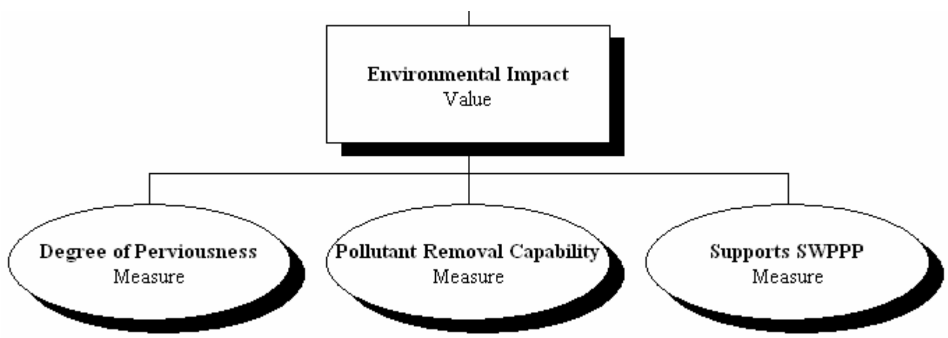


Figure 32: Evaluation Measures for *Environmental Impact*. *Environmental Impact* is measured by a pavement's ability to intercept and filter stormwater.

The overall value hierarchy is presented is Figure 33.

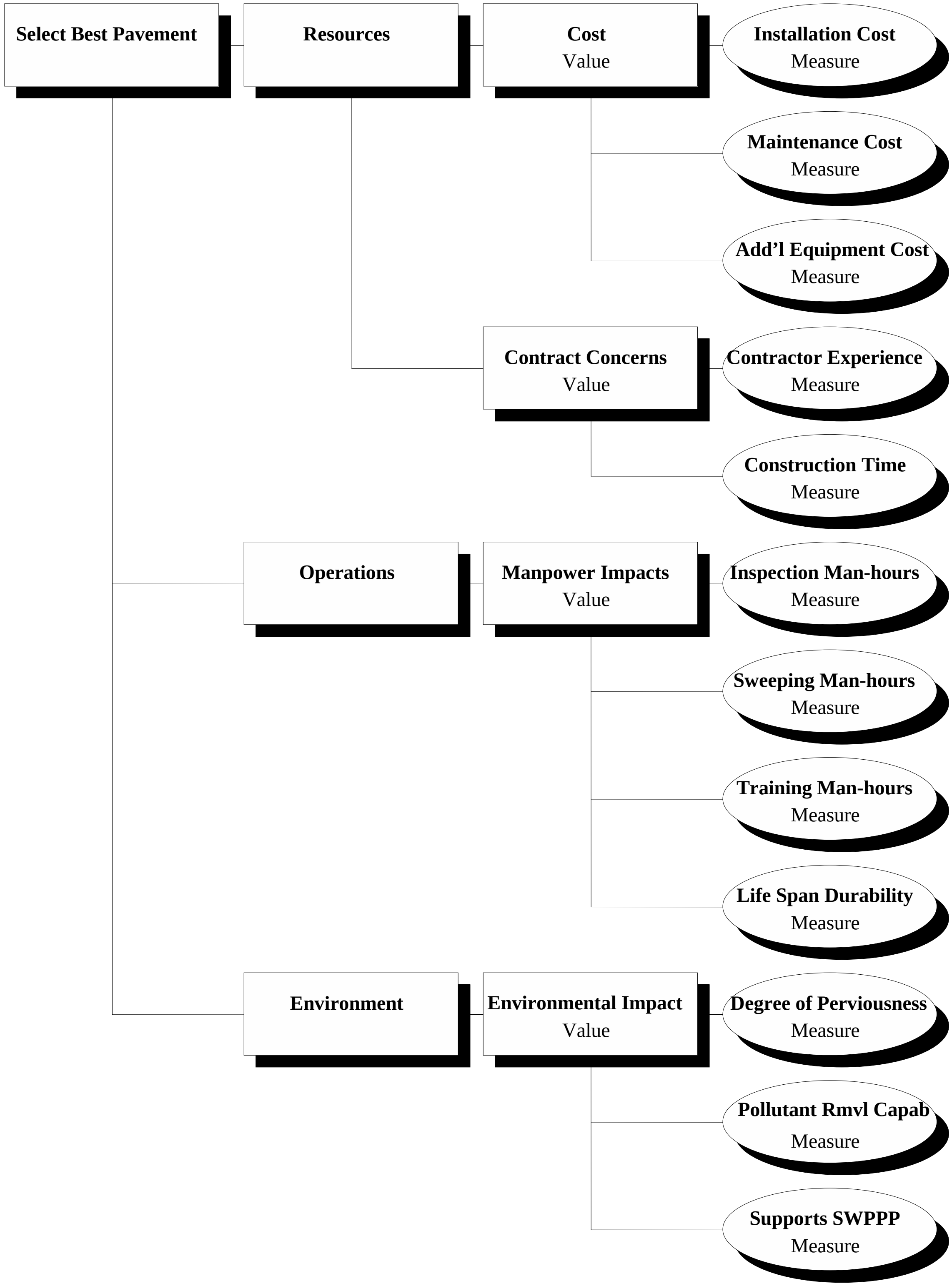


Figure 33: Overall Value Hierarchy. Alternatives will be scored using 12 evaluation measures.

3.5. Step Four: Create Single Dimension Value Functions

The next step in the VFT process is to create a Single Dimension Value Function (SDVF) for each evaluation measure. As described in Chapter 2, the purpose of an SDVF is to convert all the evaluation measures to a unitless scale where a score of one is the best and a score of zero is the worst. The SDVFs used in this model are discrete (categorical) or continuous (linearly or exponentially). A discrete SDVF has a limited number of choices (categories) while a continuous SDVF can have an infinite number of possible scores.

The SDVFs for this value model were also solicited from the decision-maker panel as they represent the subject-matter experts for Air Force pavements and environmental issues. A computer software program called *Logical Decisions for Windows* was used to simplify the process of creating SDVFs. First, the decision-makers decided whether a measure would be evaluated on a discrete or continuous scale. If a measure was to be evaluated discretely, each category was then determined and then given a value. If a measure was determined to be continuous, the decision-makers were asked to specify the upper and lower bounds as the best and worst possible scores for each measure. Then these values were entered into *Logical Decisions* along with a chosen reference point to get the specific shape of the curve. The reference points were chosen based on the decision-maker's experience and intuition about what value a specified score of a measure would receive. Since pavement design is affected by regional aspects, three separate sets of analysis will be conducted in this thesis. Three hypothetical bases (Northern, Central, and Southern AFBs) will be considered to represent varying regional conditions. The subsequent sections will discuss the SDVFs assigned to each measure at

Central AFB in detail while the SDVFs for all bases will be located in Appendices A, B, and C.

3.5.1. *Cost*

Costs for installation were set in terms of dollars per square foot. Pavement costs at Central AFB ranged from $7.13 to $13.33 per square foot. The reference point, again chosen based on the decision-maker's experience, was $8.15 per square foot with a score of (0.5). Figure 34 shows the SDVF for Installation Costs.

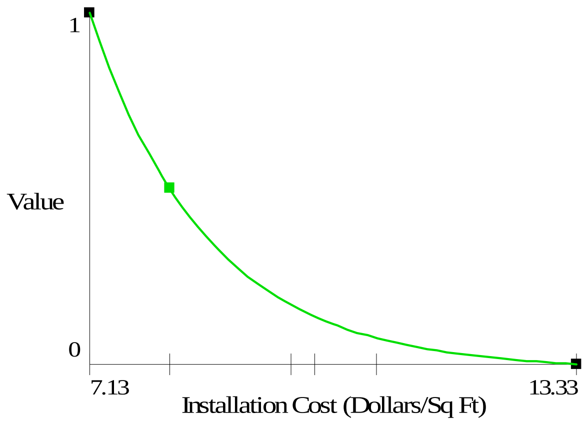


Figure 34: Installation Cost SDVF.

Costs for maintenance were set in terms of dollars per square foot per year of operation. The maintenance costs for pavements at Central AFB ranged from $0.03 to $0.07 per square foot per year. The decision-maker felt the SDVF should be linear, so the chosen reference point was $0.05 per square foot per year with a score of (0.5). Figure 35 shows the SDVF for Maintenance Costs.

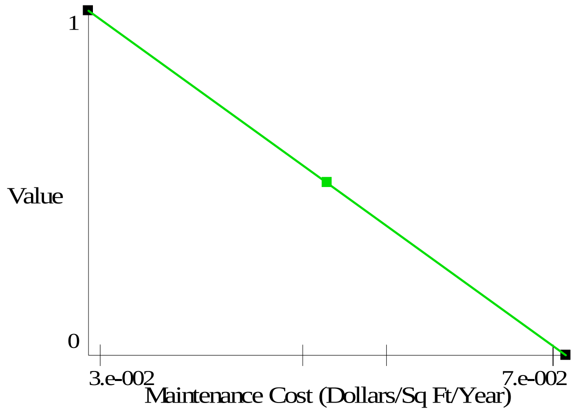


Figure 35: Maintenance Cost SDVF.

Required Equipment Cost was set in terms of thousands of dollars ($K) and those costs ranged from $0 to $200K. The reference point was $20K with a score of (0.5). Figure 36 shows the SDVF for Required Equipment Costs.

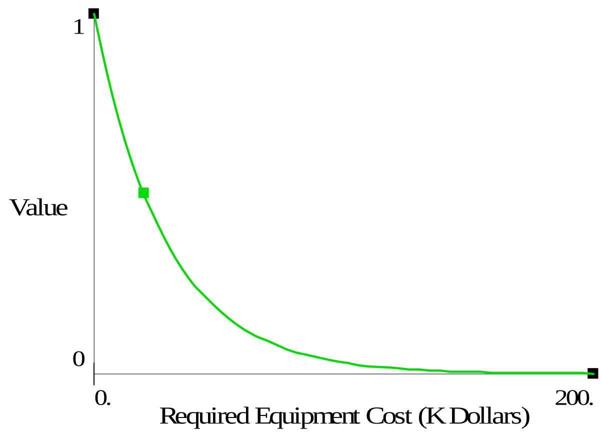


Figure 36: Required Equipment Cost SDVF.

3.5.2. *Contract Concerns*

Contractor Experience was determined to be a discrete SDVF. The categories of experience were: none, minor, adequate, and exceptional (see Figure 37). A contractor with no experience received a score of zero because there was no evidence that he could successfully complete an installation. Minor experience, a score of (0.25), meant that a

contractor had the technical ability to attempt the project but had not installed a paving system of that type before. Adequate experience meant that the contractor had successfully installed one application of that pavement type and was worth a score of (0.75). A contractor with more than one successful application was given a score of (1.0) and a rating of Exceptional.

Figure 37: Contractor Experience SDVF.

Construction Time was evaluated linearly from zero to two days per square foot. The SDVF is linear because the value associated with construction time increased linearly as construction time decreased (see Figure 38).

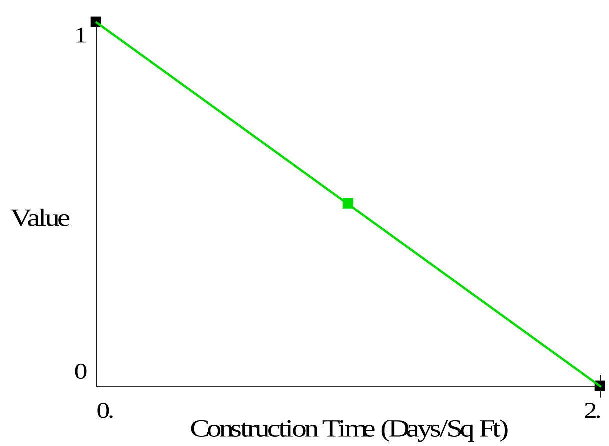


Figure 38: Construction Time SDVF.

3.5.3. ***Manpower Impact***

Inspection Man-hours was also deemed to be a discrete SDVF (see Figure 39). A pavement in the category of Low oversight would receive the top score of (1.0) because it required less oversight than conventional methods. Those conventional methods were thought to be in the Medium oversight category and given a score of (0.66). Pavements requiring a High level of oversight due to technical complexity received the lowest score of (0.33).

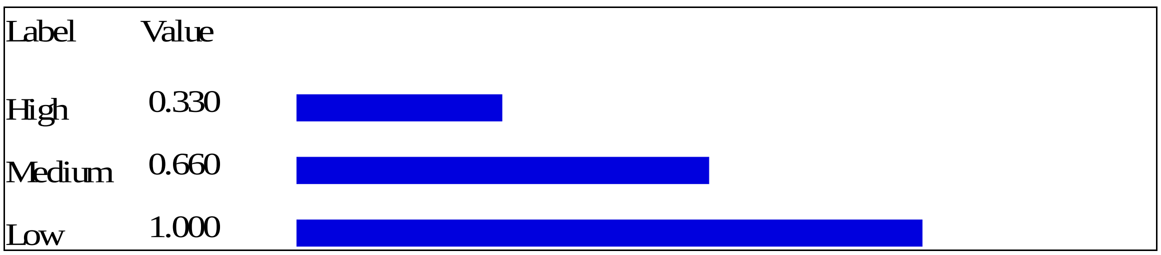


Figure 39: Inspection Man-hours SDVF.

The Sweeping Man-hours SDVF was a simple discrete measure of two categories: yes or no (see Figure 40). The category of No meant no additional man-hours would need to be expended sweeping the pavement and therefore received a score of (1.0). If any man-hours needed to be dedicated to sweeping, that alternative would receive a value of (0.0).

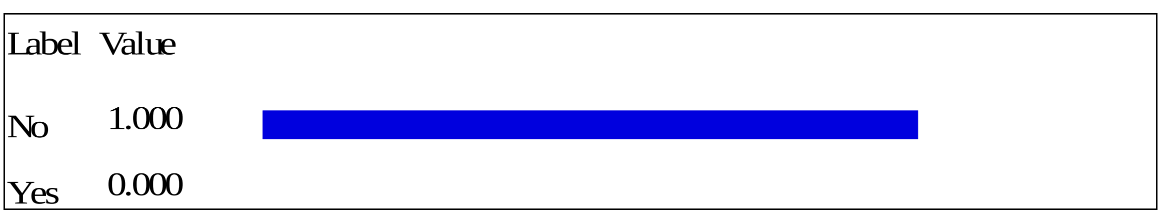


Figure 40: Sweeping Man-hours SDVF.

Training Man-hours was a continuous SDVF due to the decreasing value associated with more stringent training requirements. The decision-makers felt eight man-hours was an acceptable amount of time for training (worth a value of one), but 40 man-hours was unacceptable (a value of zero). As shown in Figure 41, the reference point for a value of (0.5) was determined to be 16 man-hours.

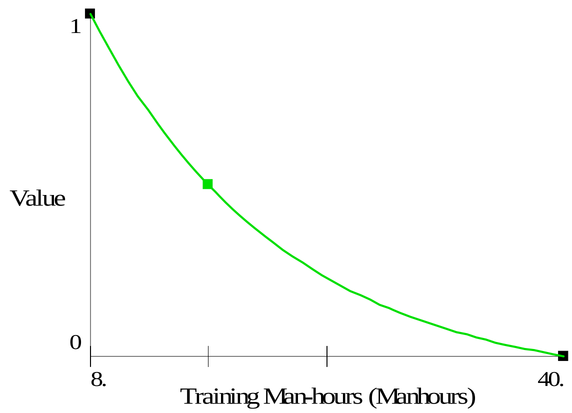


Figure 41: Training Man-hours SDVF.

Life Span Durability is measured continuously from five years to 20 years. A pavement with a life of 20 years receives the best score of (1.0) while pavements only lasting five years or less receive a score of (0.0) (see Figure 42). The reference point for a score of 0.5 was determined to be at 15 years because that is the projected life for most asphalt systems.

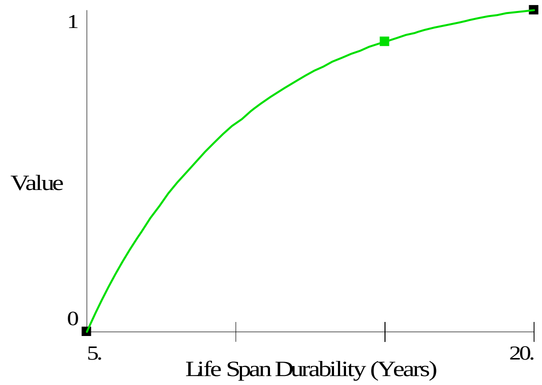


Figure 42: Life Span Durability SDVF.

3.5.4. *Environmental Impacts*

The measures of Degree of Perviousness and Pollutant Removal Capability are both evaluated as a percentage ranging from 0 to 100 percent, and are continuous but have differing shapes. The measure of Degree of Perviousness increases linearly as more stormwater is diverted away from the base infrastructure (Figure 43). Pollutant Removal Capability doesn't change linearly because the decision-maker thought there was very little value to be had until pollutants were significantly reduced. Therefore, a reference point of 70% removal was established with a value of (0.5) as shown in Figure 44.

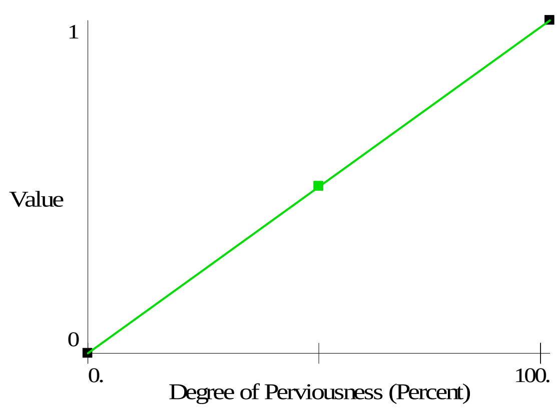


Figure 43: Degree of Perviousness SDVF.

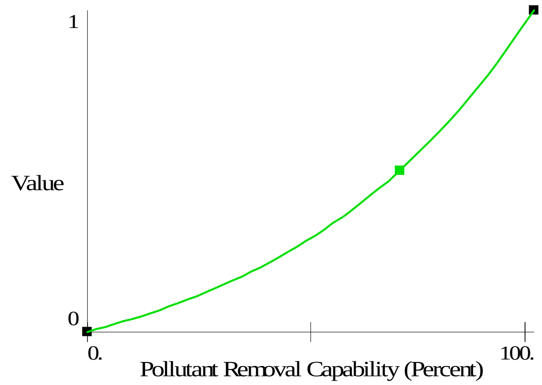


Figure 44: Pollutant Removal Capability SDVF.

The measure that takes into account whether or not the pavement supports a base's Stormwater Pollution Prevention Plan (SWPPP) is also a simple discrete SDVF (Figure 45). In order for a pavement to support the base's SWPPP, it must contribute to a pollution prevention initiative as described in the base plan. For example, if the base SWPPP indicates that the base will make every effort to reduce its stormwater runoff by 10%, a porous asphalt pavement would contribute towards the fulfillment of that goal where traditional asphalt would not. If the pavement supports the plan it receives a value of (1.0), otherwise a value of (0.0).

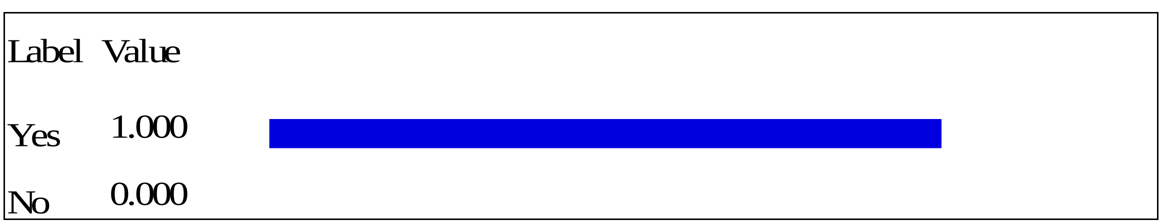


Figure 45: Support SWPPP SDVF.

3.6. Step Five: Weight Value Hierarchy

The fifth step in the VFT process is to weight the value hierarchy. As discussed in Chapter 2, weighting the hierarchy is intended to assure that measures that are more important than others have a larger effect on the total decision. In order to determine the weights across the entire hierarchy, the four means objectives were considered first. Using the 'swing weighting' technique, the decision-makers were asked to rank order the four means objectives from least preferred to most preferred. The least preferred objective, *Contract Concerns*, was then given a value of X. Each of the remaining three was then given a value in terms of how much more important they were compared to *Contract Concerns*, X. These values were summed to one and the equation was solved for X. This revealed the weight of *Contract Concerns* and then, subsequently, the weight for the remaining three means objectives. The same method that was used on each of the four means objectives was then used for their underlying measures. Table 4 shows the global weights for each of the fundamental objectives, means objectives, and measures.

Table 4: Global Weights of Each Aspect of the Value Hierarchy.

Fundamental Objective	Means Objective	Measure	Global Weight
Resources			***0.571***
	Costs		***0.472***
		Installation Cost	0.314
		Maintenance Cost	0.099
		Required Equipment Cost	0.059
	Contract Concerns		***0.099***
		Contractor Experience	0.069
		Construction Time	0.03
Operations			***0.229***
	Manpower Impact		***0.229***
		Inspection Man-hours	0.024
		Sweeping Man-hours	0.055
		Training Man-hours	0.059
		Life Span Durability	0.091
Environment			***0.200***
	Environmental Impact		***0.200***
		Degree of Perviousness	0.010
		Pollutant Removal Capability	0.010
		Supports SWPPP	0.180

3.7. Step Six: Alternative Generation

After considering a decision-maker's values, creating a value hierarchy, and then weighting that hierarchy, it was then possible to generate alternatives. The alternatives immediately generated are those conventionally used on Air Force bases: asphalt and concrete. Several unconventional, porous options will also be considered. As described in the literature review porous asphalts and concretes, paving stones, and structural turf are all good candidates for comparison against the conventional methods. Chapter 4 will use the value hierarchy, measures, and weights developed in this chapter to effectively compare these six options to determine under what conditions porous pavements may be more desirable than conventional pavements.

4. Analysis

4.1. Overview

This chapter will analyze the results produced by the model using steps seven, eight, and nine from Shoviak's 10 step VFT process. These steps involve scoring, rank ordering, and performing sensitivity analysis on all of the alternatives. Since pavement design is affected by regional aspects, three separate sets of analysis will follow. Three hypothetical bases (Northern, Central, and Southern AFBs) were considered to represent varying regional conditions. The primary differences between the scoring of these bases are found in the measures of *Installation Cost*, and *Contractor Experience*. *Installation Cost* varied considerably by region due to changes in the maximum frost depth for different areas. Typically, a deeper maximum frost depth will require a thicker base course and pavement structure to avoid frost heave. The maximum frost depths used for the three hypothetical bases are listed in Table 5 below. *Contractor Experience* also varied by region due to an increased familiarity with porous pavement systems in southern locations. All other measures were assumed to remain the same for the different locations.

Table 5. Regional Frost Depths.

REGION	MAXIMUM FROST DEPTH
Northern AFB	72"
Central AFB	38"
Southern AFB	6"

4.2. Northern AFB

Northern AFB is a hypothetical base in the northern tier of the US. Its features are modeled after the Grand Forks area of North Dakota with severe winters (average of 179

days below freezing and 40.4 inches of snowfall) and a maximum frost depth of 72" (climate-zone.com, 2003). Table 6 summarizes the assumed regional climate data for Northern AFB. The following sections will review how well the alternatives scored and ranked at this location, and how sensitive the model is to changing evaluation weights.

Table 6. Annual Climate Data for Northern AFB (climate-zone.com, 2003)

Northern AFB Annual Climate Data	
Avg. Temperature (F)	41
Avg. Max Temperature (F)	51.5
Avg. Min Temperature (F)	30.3
Days with Max Temp of 90 F or Higher	14
Days with Min Temp Below Freezing	179
Precipitation (inches)	19.4
Days with Precipitation 0.01 inch or More	100
Avg. Snowfall (inches)	40.4
Avg. Max. Frost Depth (inches)	72

4.2.1. Step Seven: Alternative Scoring at Northern AFB

The seventh step in Shoviak's process is to score each of the generated alternatives to determine how well they perform based on the evaluation measures developed in Chapter 3. In order to do this, data was collected in various ways. Cost data for conventional systems was obtained mainly through the *RS Means Assemblies Cost Data* book (Balboni, 2005) while Bruce Ferguson's *Porous Pavements* book provided much of the information for porous systems (Ferguson, 2005). Additional information regarding pavement maintenance, inspection criteria, training, and construction time was obtained through subject matter experts at the Air Force Institute of Technology, Civil Engineer and Services School. Various studies cited in the literature review (Chapter 2) also contributed to the scoring of the porous pavement alternatives. After compiling data from these multiple sources, all six alternatives (asphalt, concrete, paving stones, porous asphalt, porous concrete, and structural turf) were scored for the 12 evaluation measures as shown in Table 7.

Table 7. Alternative Scoring for Northern AFB.

MEASURES	ALTERNATIVES					
	Asphalt	*Concrete*	*Paving Stones*	*Porous Asphalt*	*Porous Concrete*	*Structural Turf*
Installation Cost ($/SF)	10.65	11.49	18.74	16.88	18.48	10.00
Maintenance Cost ($/SF/Year)	0.055	0.031	0.031	0.069	0.069	0.048
Degree of Perviousness (%)	0	0	50	98	98	98
Pollutant Removal Capability (%)	0	0	50	98	98	98
Supports SWPPP	No	No	Yes	Yes	Yes	Yes
Contractor Experience	Exceptional	Exceptional	Adequate	Minor	Minor	Minor
Construction Time	Low	High	Low	Medium	High	High
Additional Equipment Cost ($K)	0	0	0	150	150	0
Inspection Man-hours	Medium	Medium	Low	High	High	Medium
Sweeping Man-hours	No	No	No	Yes	Yes	No
Training Man-hours (Hours)	8	8	16	24	24	16
Life Span Durability (Years)	15	20	15	20	20	10

4.2.2. Step Eight: Deterministic Analysis at Northern AFB

In Chapter 3, Single-Dimension Value Functions (SDVFs) were created for each evaluation measure to convert the scores in Table 7 into values on a standardized, unitless scale from zero (least preferred) to one (most preferred). Northern AFB's individual SDVFs are also located in Appendix A. The additive value function used by the *Logical Decisions for Windows* software sums the products of these values and their pre-determined weights (see Table 4 in Chapter 3) for each evaluation measure to compute a total score for each alternative. Comparing these scores allows the decision-maker to then rank order the alternatives from best to worst based on his/her stated preferences.

Figure 46 shows the rank ordered list of alternatives from best to worst (higher values are better). For Northern AFB, structural turf is the best alternative for a newly constructed parking lot. It should be noted that the values beside each alternative are only used to rank order alternatives and do not quantify how much better one alternative is over another (Kirkwood, 1997). For example, although asphalt has a value of ~0.6 and porous concrete has a value of ~0.3; asphalt is not twice as good as porous concrete. The values only state that asphalt is a better alternative when compared to porous concrete.

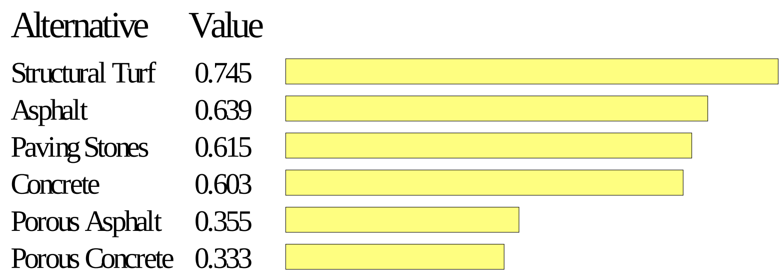


Figure 46. Northern AFB Alternative Rankings.

Figure 47 shows the ranked alternatives in terms of how well they fulfilled each of the decision-maker's fundamental objectives. The color-coded bars indicate how much value an alternative gained for how well it fulfilled each fundamental objective. Comparing the alternatives, it's easy to see where alternatives are stronger or weaker than their competitors. The top choice, structural turf, gained the least amount of value for the *Operations* objective but made up for it with high values for *Resources* and *Environment*. Asphalt and concrete gained zero value for *Environment* but still ranked well due to high scores for *Resources* and *Operations*.

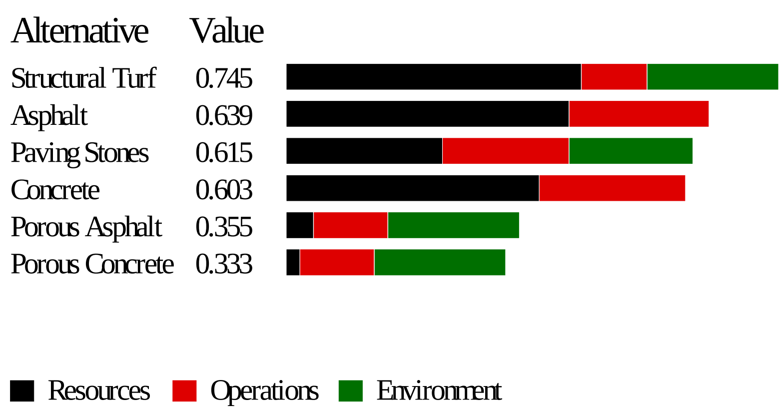


Figure 47. Overall Rankings with Respect to Fundamental Objectives.

The *Logical Decisions for Windows* software carries the deterministic analysis one step further by also examining how much value individual measures contributed to

the rankings of each alternative. Figure 48 quickly shows the user which measures help or hurt the rankings of each alternative. At Northern AFB, structural turf gains more value than any other alternative for the measure of installation cost. The reason for this is that all other pavement systems are susceptible to frost heave and must add supplementary pavement and/or deeper base course material to compensate. Since installation cost carries the most weight in the model, structural turf gained a serious advantage by presenting the cheapest installation cost.

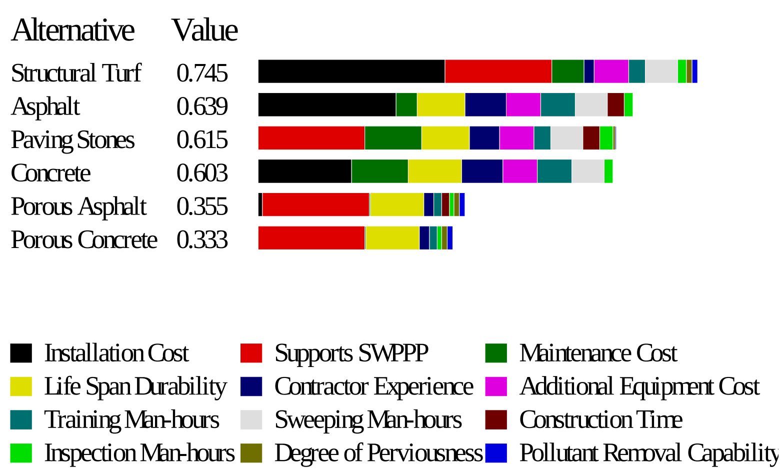


Figure 48. Overall Rankings with Respect to Evaluation Measures.

4.2.3. Step Nine: Sensitivity Analysis at Northern AFB

Sensitivity analysis is a method of verifying that the model is built on proper assumptions. One of the biggest assumptions in the model is that the evaluation measures have been given the proper weighting and accurately depict the decision-maker's preferences. Sensitivity analysis helps the decision-maker verify these weightings by showing how the ranking of alternatives may change based on variations in measure weights.

This type of sensitivity analysis begins by moving a selected measure's weight from zero to one, regardless of the predetermined weight. As the measure's weight changes, the weights of all other evaluation measures are proportionally adjusted to ensure all weights still sum to one. The subsequent sections will graphically demonstrate how each alternative will receive more or less value depending on the weight of the selected evaluation measure.

4.2.3.1. Sensitivity Analysis of *Resources* Objective

For Northern AFB, sensitivity analysis was first conducted on the fundamental objective of *Resources*. As shown in Figure 49, the decision-maker originally designated *Resources* to have a weight of 0.571, indicated by the vertical line. Where the alternatives cross this line indicate their respective rankings; alternatives toward the top of the line are better than those at the bottom. Structural turf was deterministically found to be the best alternative for Northern AFB. By visual inspection, the decision-maker can see that structural turf will always be the number one choice unless the weight of *Resources* drops below 0.333, at which point paving stones become the top alternative. Changing the weight of *Resources* does impact the second alternative in that asphalt is the second choice from 0.550 to one, but paving stones could be the second choice if the weight drops slightly. Paving stones are currently the third option, but would drop to fourth (replaced by concrete) if the *Resources* weight rose to 0.600.

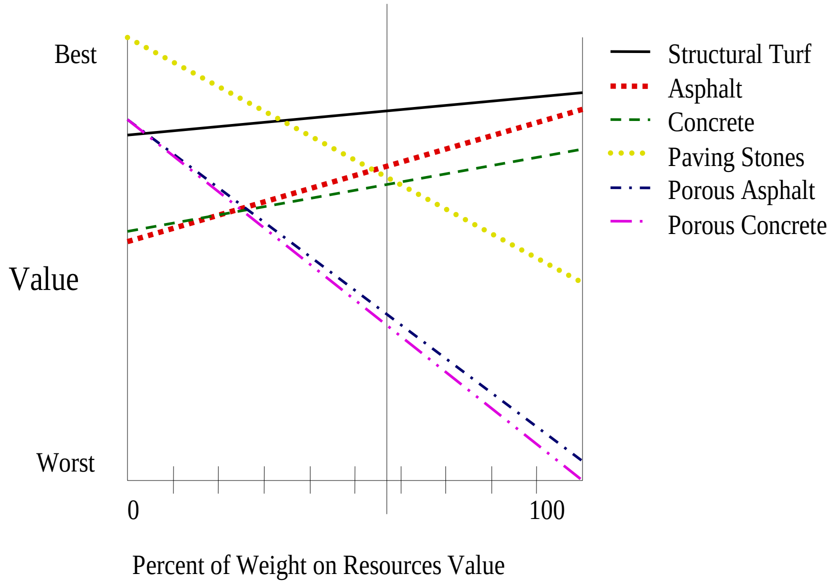


Figure 49. Sensitivity Analysis for *Resources* at Northern AFB.

4.2.3.2. Sensitivity Analysis of Operations Objective

Next, sensitivity analysis was conducted on the fundamental objective of *Operations*. As shown in Figure 50, the decision-maker originally designated *Operations* to have a weight of 0.229. Structural turf is shown to be the best choice as long as the weight of *Operations* is less than 0.333, or 33% of the decision. If the weight is between 0.333 and 0.600, asphalt is the number one alternative, but between 0.600 and one, concrete is the top choice. This sensitivity analysis suggests that as long as the *Operations* weight is low (below 33%), structural turf is the best choice. However, as *Operations* becomes more important, structural turf rapidly drops in the rankings, eventually becoming the worst alternative while conventional asphalt and concrete rise to the top.

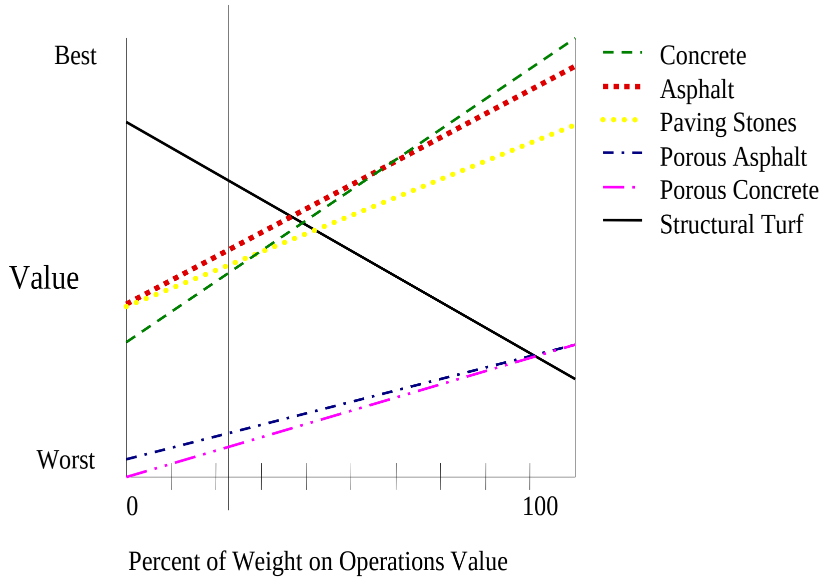


Figure 50. Sensitivity Analysis for *Operations* at Northern AFB.

4.2.3.3. Sensitivity Analysis of *Environment* Objective

Lastly, sensitivity analysis was conducted on the fundamental objective of *Environment*. As shown in Figure 51, the decision-maker originally designated *Environment* to have a weight of 0.200. Structural turf is shown to be the best choice as long as the weight of *Environment* is greater than 0.100, or 10% of the decision. If *Environment* was less important, asphalt and concrete would become the number one and two options, respectively. However, as the importance of *Environment* increases, the value of the conventional alternatives descends to become the worst options.

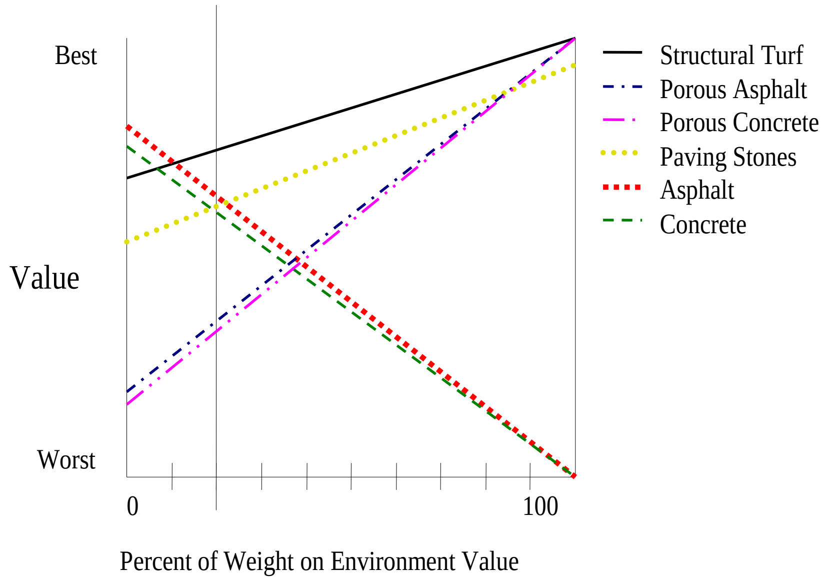


Figure 51. Sensitivity Analysis for *Environment* at Northern AFB.

4.2.3.4. Overall Sensitivity Comments for Northern AFB

Table 8 illustrates how much the current weights must change in order for another alternative to overtake structural turf. Based on the percent change required, it is apparent that although the most sensitive fundamental objective is *Resources*, it would require a 41.68% decrease in weight in order for paving stones to become the number one option. Therefore, the current model for Northern AFB is considered to be insensitive to changing weights.

Table 8. Summary of Northern AFB's Sensitivity Analysis

Fundamental Objective	Current Weight	Adjusted Weight	Percent Change Required	New Top Alternative
Resources	0.571	0.333	-41.68%	Paving Stones
Operations	0.229	0.333	45.41%	Asphalt
		0.600	162.01%	Concrete
Environment	0.200	0.100	-50.00%	Asphalt

4.3. Central AFB

As its name implies, Central AFB is a hypothetical base in the middle of the US. It differs from Northern AFB with less severe winters (less snowfall, days below freezing and maximum frost depth) and a broader range of contractor experience (climate-zone.com, 2003). Table 9 summarizes the assumed regional climate data for Central AFB. The following sections will review how well the alternatives scored and ranked at this location, and how sensitive the model is to changing evaluation weights.

Table 9. Annual Climate Data for Central AFB (climate-zone.com, 2003)

Central AFB Annual Climate Data	
Avg. Temperature (F)	33.9
Avg. Max Temperature (F)	41.7
Avg. Min Temperature (F)	26
Days with Max Temp of 90 F or Higher	0
Days with Min Temp Below Freezing	22
Precipitation (inches)	3
Days with Precipitation 0.01 inch or More	9
Avg. Snowfall (inches)	3.8
Avg. Max. Frost Depth (inches)	38

4.3.1. Step Seven: Alternative Scoring at Central AFB

Table 10 summarizes how each alternative scored for the evaluation measures at Central AFB.

Table 10. Alternative Scoring for Central AFB.

	ALTERNATIVES					
MEASURES	*Asphalt*	*Concrete*	*Paving Stones*	*Porous Asphalt*	*Porous Concrete*	*Structural Turf*
Installation Cost ($/SF)	7.13	8.15	13.33	9.7	10.79	10.00
Maintenance Cost ($/SF/Year)	0.055	0.031	0.031	0.069	0.069	0.048
Degree of Perviousness (%)	0	0	50	98	98	98
Pollutant Removal Capability (%)	0	0	50	98	98	98
Supports SWPPP	No	No	Yes	Yes	Yes	Yes
Contractor Experience	Exceptional	Exceptional	Adequate	Adequate	Minor	Adequate
Construction Time	Low	High	Low	Medium	High	High
Additional Equipment Cost ($K)	0	0	0	150	150	0
Inspection Man-hours	Medium	Medium	Low	High	High	Medium
Sweeping Man-hours	No	No	No	Yes	Yes	No
Training Man-hours (Hours)	8	8	16	24	24	16
Life Span Durability (Years)	15	20	15	20	20	10

4.3.2. Step Eight: Deterministic Analysis at Central AFB

Using the scores summarized in Table 10 and the predetermined SDVFs (see Chapter 3 or Appendix B), conventional asphalt was found to be the top alternative for Central AFB with a value of 0.721. Paving stones were the second alternative with a value of 0.615. Figure 52 shows the rankings and values for all the alternatives at Central AFB.

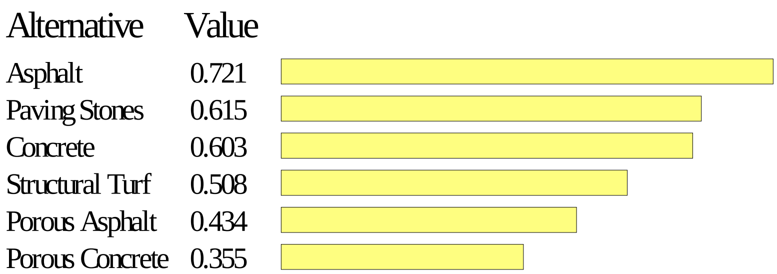


Figure 52. Central AFB Alternative Rankings.

Figure 53 illustrates how well each alternative scored in terms of the fundamental objectives of *Resources*, *Operations*, and *Environment*. Although asphalt received no value from *Environment*, it still ranked number one due to having the best score in *Resources*. Structural turf, the top option for Northern AFB, scored very poorly in both *Resources* and *Operations* at Central AFB, causing it to rank fourth overall.

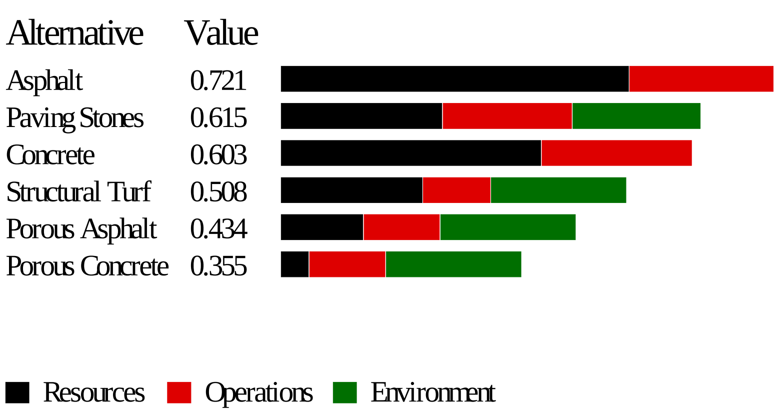


Figure 53. Overall Rankings with Respect to Fundamental Objectives.

When looking at the value contributions of individual evaluation measures, it becomes clearer which measures differentiated the alternatives from one another. Figure 54 shows how well each alternative performed for the 12 evaluation measures. Asphalt's main advantage was in its superior score under installation cost despite a score of zero for not supporting the base SWPPP. Conversely, paving stones received no value for installation cost but scored well for SWPPP support.

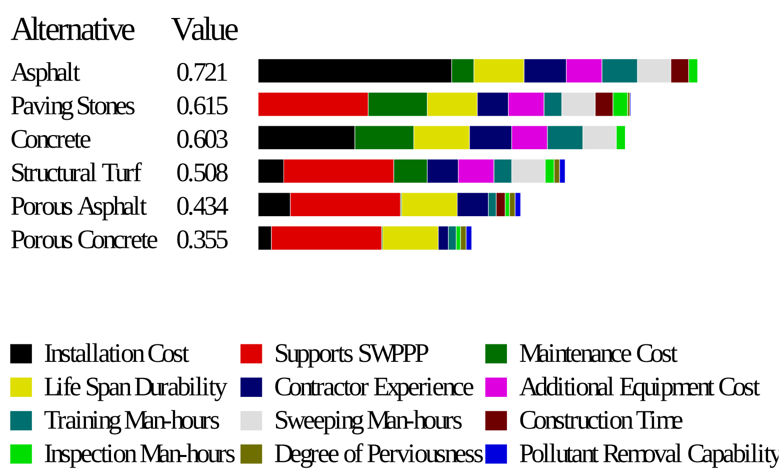


Figure 54. Overall Rankings with Respect to Evaluation Measures.

4.3.3. Step Nine: Sensitivity Analysis at Central AFB

In order to determine if the model for Central AFB is sensitive to changes in the weights of evaluation measures, sensitivity analysis was conducted in the same manner as described for Northern AFB.

4.3.3.1. Sensitivity Analysis of *Resources* Objective

For Central AFB, sensitivity analysis was first conducted on the fundamental objective of *Resources*. As shown in Figure 55, the decision-maker originally designated *Resources* to have a weight of 0.571. Asphalt was deterministically found to be the best

alternative for Northern AFB. By visual inspection, the decision-maker can see that asphalt will always be the number one choice unless the weight of *Resources* drops below 0.450, at which point paving stones become the top alternative.

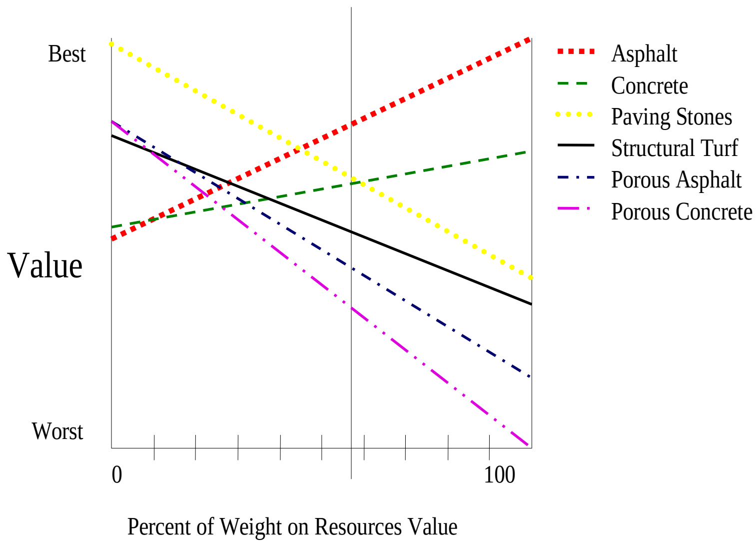


Figure 55. Sensitivity Analysis for *Resources* at Central AFB.

4.3.3.2. Sensitivity Analysis of *Operations* Objective

Next, sensitivity analysis was conducted on the fundamental objective of *Operations*. As shown in Figure 56, the decision-maker originally designated *Operations* to have a weight of 0.229. Asphalt is shown to be the best choice as long as the weight of *Operations* is less than 0.785, or 79% of the decision. If the weight of Operations is greater than 0.79, concrete is the best alternative.

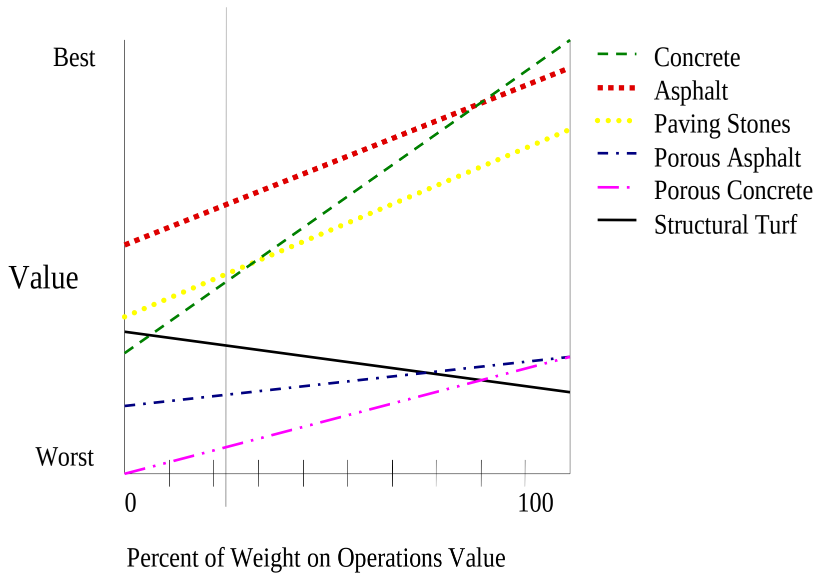


Figure 56. Sensitivity Analysis for *Operations* at Central AFB.

4.3.3.3 Sensitivity Analysis of *Environment* Objective

Lastly, sensitivity analysis was conducted on the fundamental objective of *Environment*. As shown in Figure 57, the decision-maker originally designated *Environment* to have a weight of 0.200. Asphalt is shown to be the best choice as long as the weight of *Environment* is less than 0.285. If the weight was between 0.285 and 0.700, paving stones would be the top option. Above 0.700, structural turf would again become the best alternative. It should also be noted that if *Environment* was only slightly less important, concrete would become the number two option. Again, as the importance of *Environment* increases, the value of the conventional alternatives decreases.

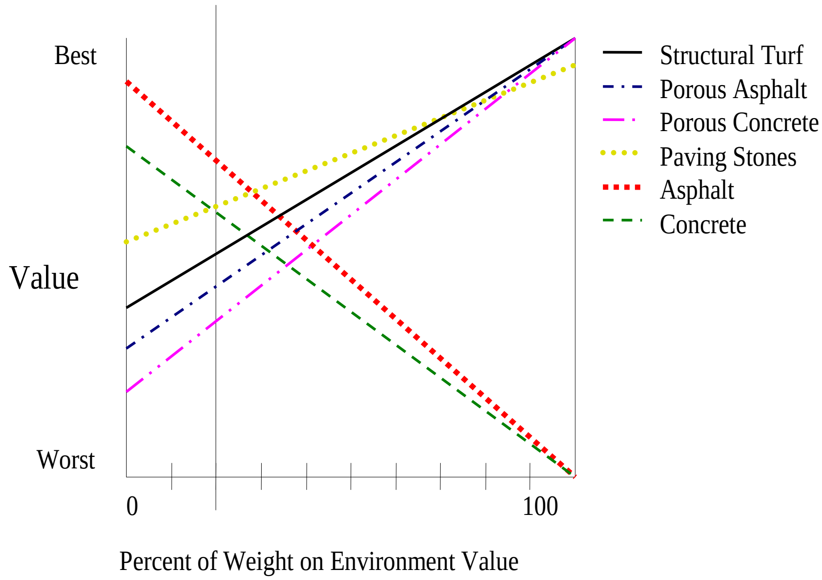


Figure 57. Sensitivity Analysis for *Environment* at Central AFB.

4.3.3.4 Overall Sensitivity Comments for Central AFB

Table 11 illustrates how much the current weights must change in order for another alternative to outrank asphalt. Similar to Northern AFB, the most sensitive fundamental objective is *Resources*. In order to replace asphalt as the top choice, *Resources* would require a 21.19% decrease in weight for paving stones to become the number one option. Therefore, the current model for Central AFB is considered to be insensitive to changing weights.

Table 11. Summary of Central AFB's Sensitivity Analysis.

Fundamental Objective	Current Weight	Adjusted Weight	Percent Change Required	New Top Alternative
Resources	0.571	0.450	-21.19%	Paving Stones
Operations	0.229	0.785	242.79%	Concrete
Environment	0.200	0.285	42.50%	Paving Stones
		0.700	250.00%	Structural Turf

4.4. Southern AFB

Southern AFB is a hypothetical base in the southeast region of the US. It differs from Northern AFB and Central AFB in that it experiences very mild winters (negligible snowfall and frost depths) and also has a broader range of contractor experience. Table 12 summarizes the assumed regional climate data for Southern AFB. The following sections will review how well the alternatives scored and ranked at this location, and how sensitive the model is to changing evaluation weights.

Table 12. Annual Climate Data for Southern AFB (climate-zone.com, 2003)

Southern AFB Annual Climate Data	
Avg. Temperature (F)	67.7
Avg. Max Temperature (F)	76.5
Avg. Min Temperature (F)	58.8
Days with Max Temp of 90 F or Higher	59
Days with Min Temp Below Freezing	16
Precipitation (inches)	62.2
Days with Precipitation 0.01 inch or More	110
Avg. Snowfall (inches)	0.2
Avg. Max. Frost Depth (inches)	6

4.4.1. Step Seven: Alternative Scoring at Southern AFB

Table 13 summarizes how each alternative scored for the evaluation measures at Southern AFB.

Table 13. Alternative Scoring for Southern AFB.

	ALTERNATIVES					
MEASURES	*Asphalt*	*Concrete*	*Paving Stones*	*Porous Asphalt*	*Porous Concrete*	*Structural Turf*
Installation Cost ($/SF)	4.32	5.45	9.82	5.47	6.44	10.00
Maintenance Cost ($/SF/Year)	0.055	0.031	0.031	0.069	0.069	0.048
Degree of Perviousness (%)	0	0	50	98	98	98
Pollutant Removal Capability (%)	0	0	50	98	98	98
Supports SWPPP	No	No	Yes	Yes	Yes	Yes
Contractor Experience	Exceptional	Exceptional	Adequate	Adequate	Exceptional	Adequate
Construction Time	Low	High	Low	Medium	High	High
Additional Equipment Cost ($K)	0	0	0	150	150	0
Inspection Man-hours	Medium	Medium	Low	High	High	Medium
Sweeping Man-hours	No	No	No	Yes	Yes	No
Training Man-hours (Hours)	8	8	16	24	24	16
Life Span Durability (Years)	15	20	15	20	20	10

4.4.2. Step Eight: Deterministic Analysis at Southern AFB

Using the scores summarized in Table 13 and the predetermined SDVFs (see Appendix C), conventional asphalt was found to be the top alternative for Southern AFB with a value of 0.721. Paving stones were the second alternative with a value of 0.615. Figure 58 shows the rankings and values for all the alternatives at Southern AFB.

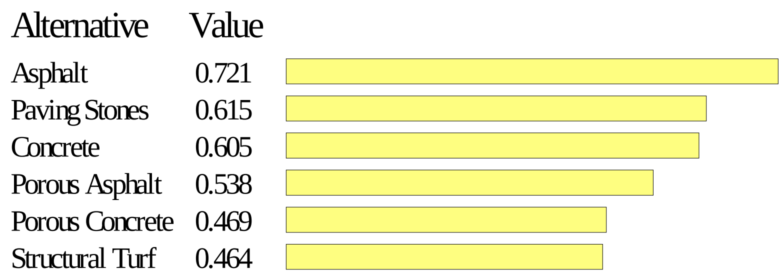


Figure 58. Southern AFB Alternative Rankings.

Figure 59 shows how well the alternatives scored on fundamental objectives: *Resources*, *Operations*, and *Environment*. As seen at Central AFB, although asphalt received no value from *Environment*, it still ranked number one due to having the best score in *Resources*. Also, concrete narrowly missed the second ranking without receiving any value for *Environment*.

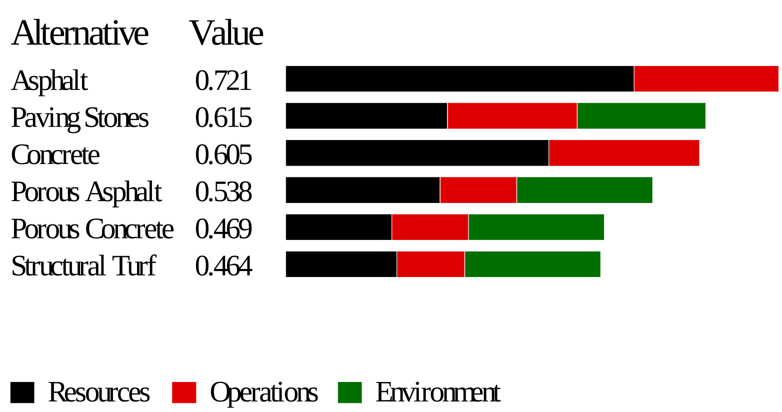


Figure 59. Overall Rankings with Respect to Fundamental Objectives.

Figure 60 summarizes how well each alternative scored for each evaluation measure. Again, installation cost offered a great advantage to asphalt to offset its lack of support to the base SWPPP and paving stones received no value for installation cost but scored well for SWPPP support. Structural turf also scored well for supporting the SWPPP and poorly for high installation costs. Additionally, it was its shorter life span durability and higher maintenance costs that made it the least desirable alternative.

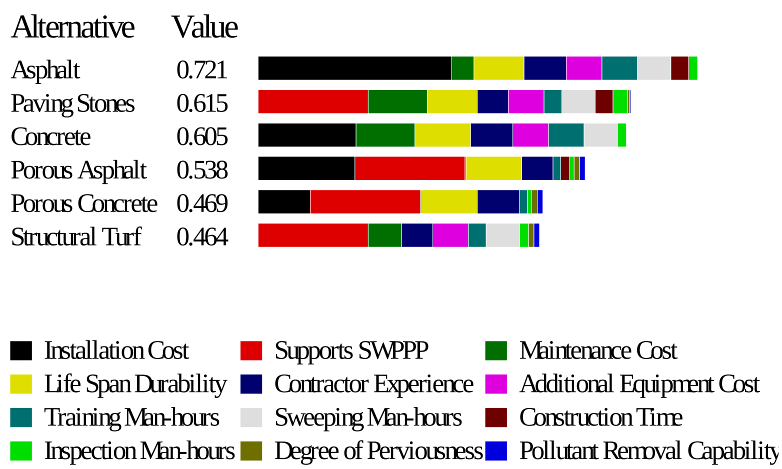


Figure 60. Overall Rankings with Respect to Evaluation Measures.

4.4.3. Step Nine: Sensitivity Analysis at Southern AFB

In order to determine if the model for Southern AFB was sensitive to changes in the weights of evaluation measures, sensitivity analysis was conducted in the same manner as described for Northern and Central AFBs.

4.4.3.1 Sensitivity Analysis of *Resources* Objective

For Southern AFB, sensitivity analysis was first conducted on the fundamental objective of *Resources*. As shown in Figure 61, the decision-maker originally designated *Resources* to have a weight of 0.571. Asphalt was deterministically found to be the best alternative for Southern AFB. By looking at Figure 61, the decision-maker can see that

asphalt will always be the number one choice unless the weight of *Resources* drops below 0.450, at which point paving stones become the top alternative. Although paving stones are currently ranked second, a small increase in the weight of *Resources* would make concrete the second choice. Overall, conventional alternatives become more favorable when the weight of *Resources* increases and porous alternatives are more preferable when the weight of *Resources* is significantly lower.

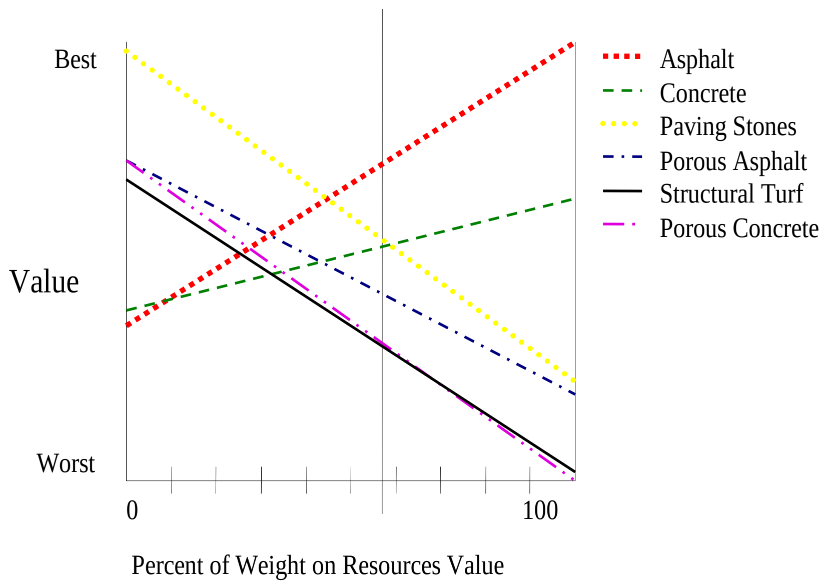


Figure 61. Sensitivity Analysis for *Resources* at Southern AFB.

4.4.3.2 Sensitivity Analysis of *Operations* Objective

Sensitivity analysis was then conducted on the fundamental objective of *Operations*. As shown in Figure 62, the decision-maker originally designated *Operations* to have a weight of 0.229. Again, conventional asphalt was shown to be the best alternative as long as the weight of *Operations* was less than 0.800, or 80% of the decision. After this point, conventional concrete becomes the number one choice. It should be noted the second ranked alternative, paving stones, would remain in second

place if the weight of *Operations* were to decrease but would become the third ranked alternative if the weight were to increase.

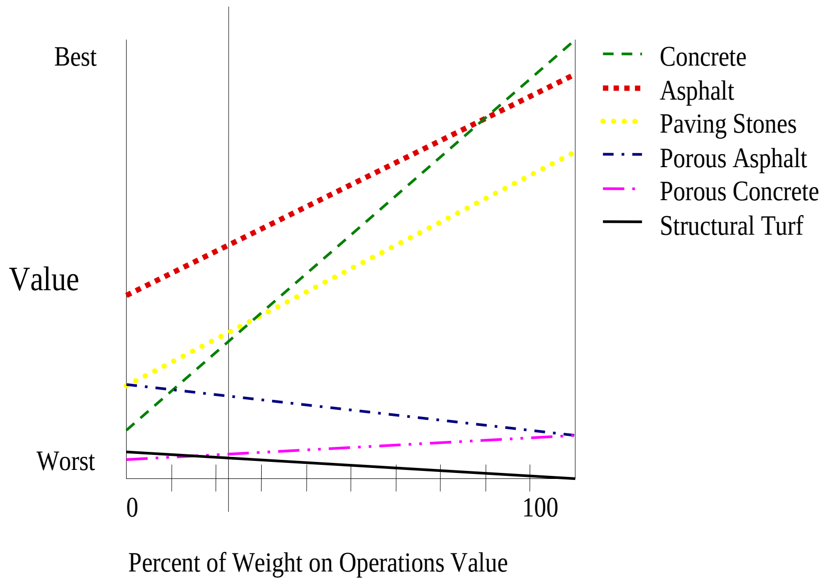


Figure 62. Sensitivity Analysis for *Operations* at Southern AFB.

4.4.3.3 Sensitivity Analysis of *Environment* Objective

Lastly, sensitivity analysis was conducted on the fundamental objective of *Environment*. As shown in Figure 63, the decision-maker originally designated *Environment* to have a weight of 0.200. Asphalt was shown to be the best choice as long as the weight of *Environment* was less than 0.290. If the weight was between 0.290 and 0.650, paving stones would be the top option. Above 0.650, porous asphalt becomes the best alternative. It should also be noted that if *Environment* was only slightly less important, concrete would become the number two option rather than paving stones. As expected, as the importance of *Environment* increases, the value of the conventional alternatives decreases and the value of porous alternatives increases.

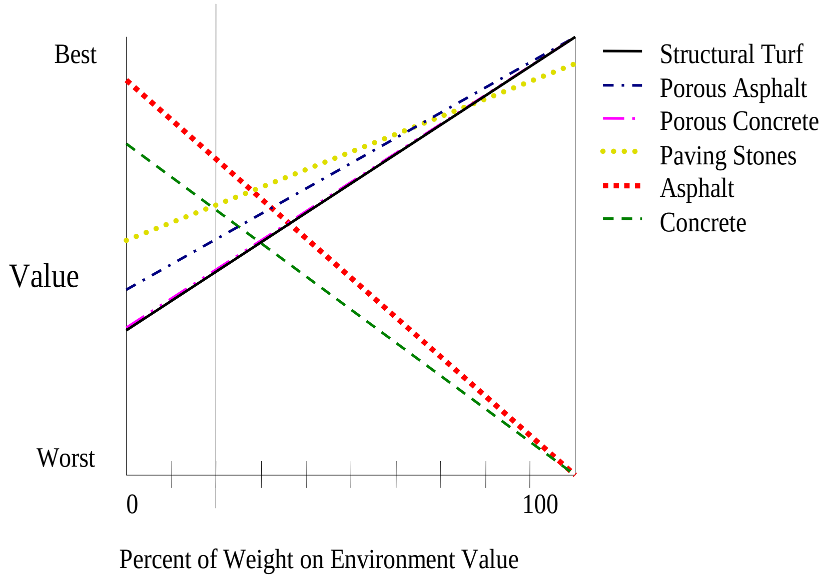


Figure 63. Sensitivity Analysis for *Environment* at Southern AFB.

4.4.3.4 Overall Sensitivity Comments for Southern AFB

Table 14 illustrates how much the current weights must change in order for another alternative to replace asphalt as the top choice. As seen at Northern and Central AFBs, the most sensitive fundamental objective is *Resources*. However, a 21.19% decrease in the weight of *Resources* would be required before allowing paving stones to become the number one option. Therefore, the current model for Southern AFB is not considered to be sensitive to changing weights.

Table 14. Summary of Southern AFB's Sensitivity Analysis.

Fundamental Objective	Current Weight	Adjusted Weight	Percent Change Required	New Top Alternative
Resources	0.571	0.450	-21.19%	Paving Stones
Operations	0.229	0.800	249.34%	Concrete
Environment	0.200	0.290	45.00%	Paving Stones
		0.650	225.00%	Porous Asphalt

5. Summary and Conclusions

5.1. Overview

The purpose of this research effort was to evaluate the feasibility of using porous pavements in lieu of conventional pavements for parking areas on Air Force installations using a Value-Focused Thinking (VFT) approach. The final step in Shoviak's 10 step VFT process is to set forth conclusions and make recommendations. This section will summarize the research questions answered by this thesis, discuss the benefits and limitations of the value model, describe future research possibilities, and make final recommendations.

5.2. Research Summary

At the start of this research effort, several questions were identified regarding the use of porous pavements on Air Force installations. Those questions are summarized in Table 15.

Table 15. Summary of Research Questions.

	Research Questions
1	What are the characteristics, benefits, and disadvantages associated with different types of porous pavements?
2	Where have porous pavements been used successfully in the past?
3	What are the environmental and economic impacts of stormwater discharges from urban areas?
4	What is the appropriate methodology for choosing to construct a parking lot from a porous pavement rather than a conventional pavement?
5	What is important to Air Force decision-makers when selecting paving options?

“What are the characteristics, benefits, and disadvantages associated with different types of porous pavements?” was the first question to be answered. Porous pavements can be characterized as a pavement that performs the same functions of a conventional pavement while maintaining a permeable surface for precipitation to infiltrate through. In general, porous pavements help reduce stormwater volumes, reduce stormwater pollutants, increase groundwater recharge and improve soil aeration. Specific types can also reduce urban heating, and improve highway safety with greater skid resistance, increased visibility, and reduced hydroplaning potential. Disadvantages to be considered with porous pavements include higher installation costs, increased maintenance requirements to maintain permeability, and lack of experienced contractors.

“Where have porous pavements been used successfully in the past?” Porous pavements have been used extensively in Europe since the 1970’s with much success. American experiences date back to the 1980’s, mainly in the coastal and south-eastern areas. However, porous pavements in the US have experienced a very high rate of failure due to improper design and/or lack of necessary maintenance. With proper maintenance, porous pavements are best suited for southern climates with moderate amounts of rainfall and highly permeable soils. Northern applications are also possible but require design modifications that can frequently cause additional costs for the original installation.

The third research question was “What are the environmental and economic impacts of stormwater discharges from urban areas?” Stormwater from urban areas has been shown to contain high levels of suspended solids, heavy metals, and hydrocarbons that can negatively affect downstream ecosystems. The increasing impervious surfaces associated with these urban areas can create large stormwater outflows during large

storms causing downstream erosion, flooding, and landslides. Economically, municipal areas must now comply with NPDES permitting regulations requiring expenditures for collection and treatment facilities, and installation of structural BMPs to reduce stormwater. Permitting and non-compliance fees are also possible.

"What is the appropriate methodology for choosing to construct a parking lot from a porous pavement rather than a conventional pavement?" Value-Focused Thinking was determined to be the best methodology to evaluate pavement options. VFT was selected due to the fact that there are competing objectives when trying to select a pavement. Often, a decision-maker will need to balance environmental considerations with economics when choosing a pavement; VFT offers an objective tool to do this. The VFT process ensures that the decision-maker's values are identified early in the process to seek a solution that best meets his/her needs.

The last research question was "What is important to Air Force decision-makers when selecting paving options?" First, Air Force decision-makers require a pavement system that can be installed quickly and correctly with minimal installation and maintenance costs. Another important consideration is how much of a manpower strain a pavement will have on base engineering personnel. Air Force decision-makers prefer pavements that do not require many man-hours for training, inspection, and maintenance. Lastly, a pavement with a minimal impact on the environment is preferable, especially if the base has a SWPPP that requires the reduction of stormwater or use of BMPs.

5.3. Value Model Benefits

The VFT model created by this research provides numerous benefits for the problem of choosing between porous and conventional paving systems. First, the VFT

process provides an objective tool that offers a systematic, quantitative approach to decision-making. By asking the Air Force decision-makers to first identify their values before any alternatives are identified, all possible alternatives were identified and considered without bias, rather than just choosing the status quo. By utilizing VFT, the decision-maker choosing a pavement system can take a proactive, strategic approach to pavement selection ensuring proper attention is paid to those objectives that are truly important. The structure of the values and measures in the model gives insight into why certain alternatives perform better than others, and sensitivity analysis shows the decision-maker how changes in weights can affect the rankings of those alternatives.

5.4. Model Limitations

The VFT model created in this thesis was based on several assumptions. The model is specifically designed for locations experiencing moderate amounts of rainfall and having soils with an acceptable degree of permeability. If these conditions are not met, the model is still effective but attention would be required in adjusting installation costs to reflect additional design changes to compensate for poor soil permeability or excessive rainfall. Another limitation is the lack of consistent cost data for the porous materials. The numbers used in the model were based on the synthesis of various sources from the literature review and may not be completely accurate in today's economy; more concise cost estimates may affect the model's rankings. Also, the weight of Environmental Impact may change based on location-specific conditions and politics.

5.5. Future Research

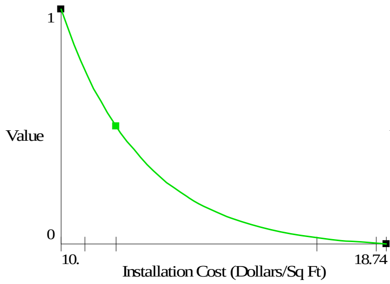
As mentioned in the previous section, more accurate estimations of porous paving methods are needed to validate the costs used in this model. Also, long-term performance studies should also verify the functionality of porous pavements for extended periods of time given the proper design and maintenance. Particularly necessary is additional study of cold weather performance of all porous pavement types. As environmental regulations and concerns change over time, the weights developed for this model may also change and should therefore be reviewed periodically to ensure the values contained within still represent the current values.

5.6. Conclusions

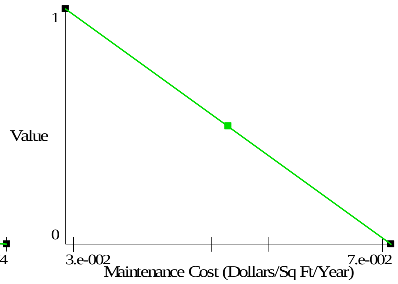
This research shows that value-focused thinking is an appropriate methodology for comparing conventional and porous pavements for Air Force parking areas. Also, porous pavements have been shown to have numerous environmental and safety benefits over conventional options. However, with today's costs and environmental regulations, porous pavements should only be chosen over conventional asphalt in very limited situations. The model indicates that structural turf is the best alternative in Northern locations due to its resistance to frost heave. Conventional asphalt remains the best alternative for all other locales. In the future, as familiarity with porous systems increases, installation costs drop, and environmental concerns rise, the model shows that porous systems will be superior alternatives when compared to conventional asphalt or concrete.

Appendix A: Northern AFB

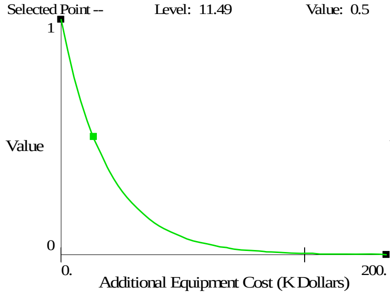
Single Dimension Value Functions:



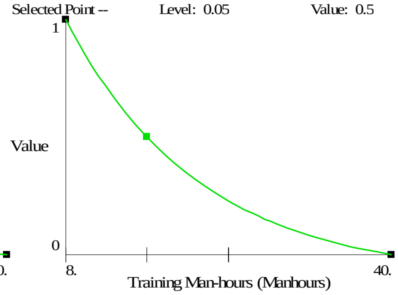
Selected Point -- Level: 11.49 Value: 0.5



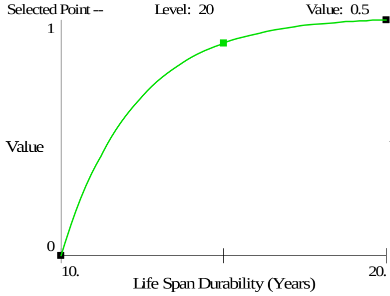
Selected Point -- Level: 0.05 Value: 0.5



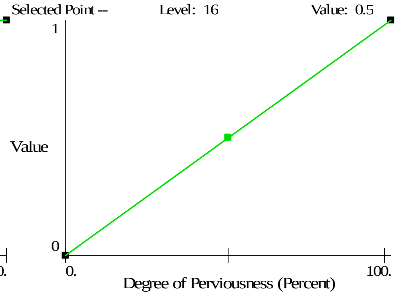
Selected Point -- Level: 20 Value: 0.5



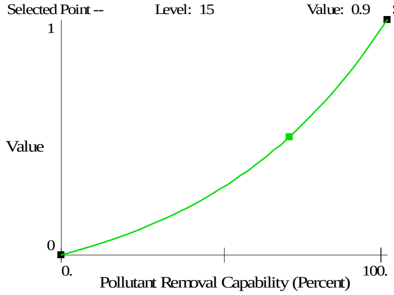
Selected Point -- Level: 16 Value: 0.5



Selected Point -- Level: 15 Value: 0.9



Selected Point -- Level: 50 Value: 0.5



Selected Point -- Level: 70 Value: 0.5

Contractor Experience

Construction Time

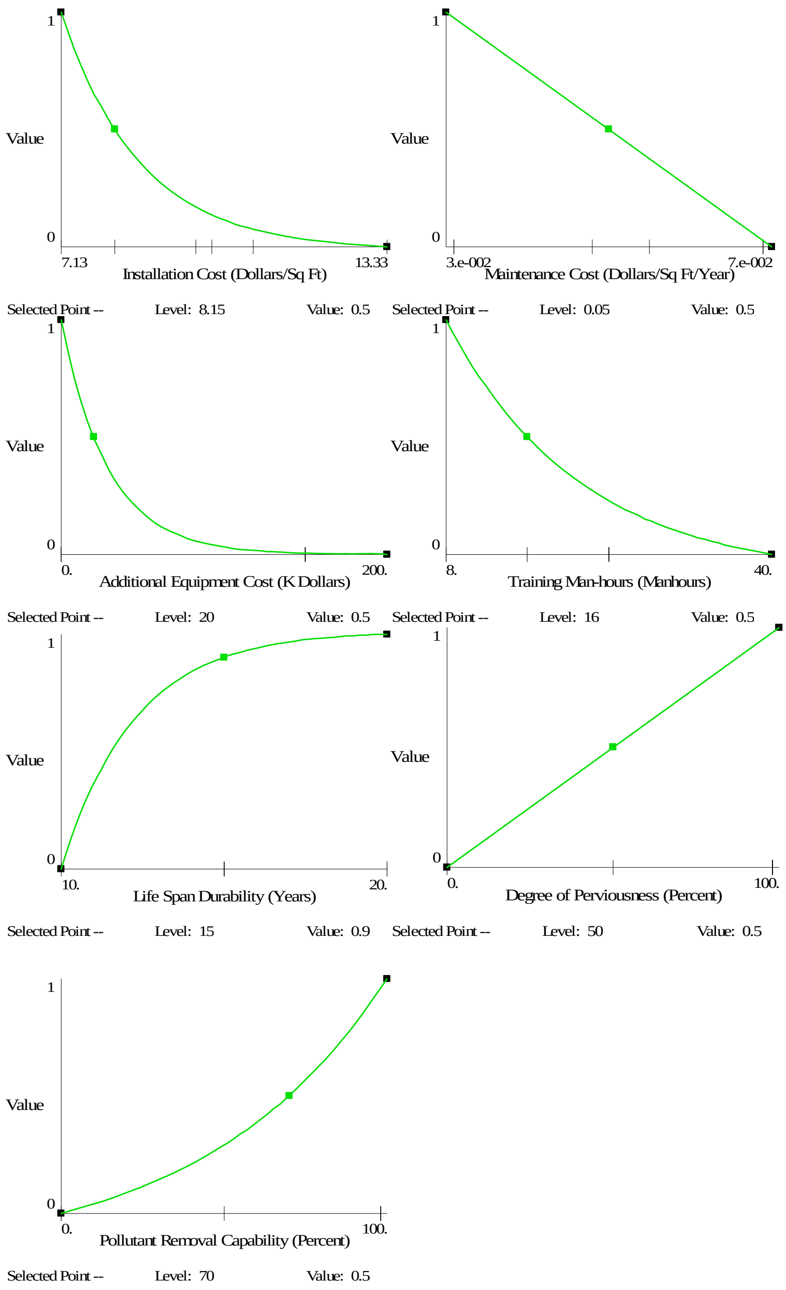
Inspection Man-hours

Sweeping Man-Hours

Supports SWPPP

Appendix B: Central AFB

Single Dimension Value Functions:



Contractor Experience

Construction Time

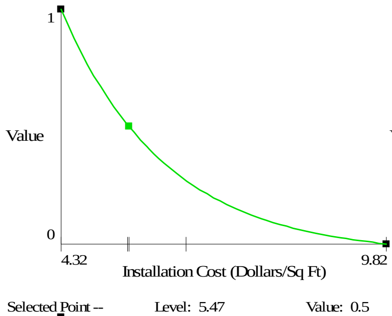
Inspection Man-hours

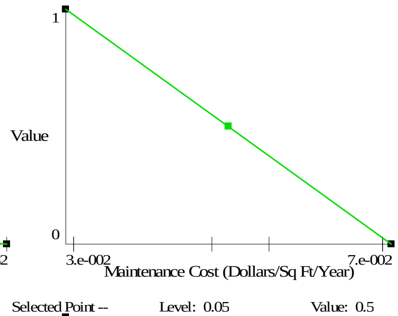
Sweeping Man-hours

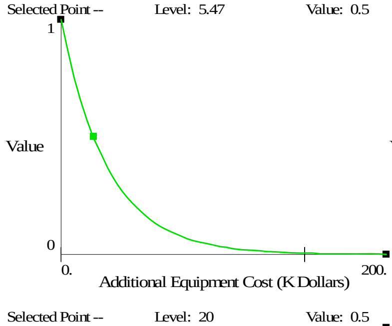
Supports SWPPP

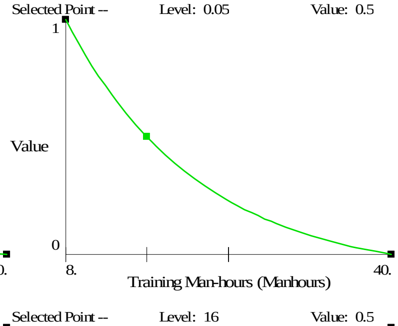
Appendix C: Southern AFB

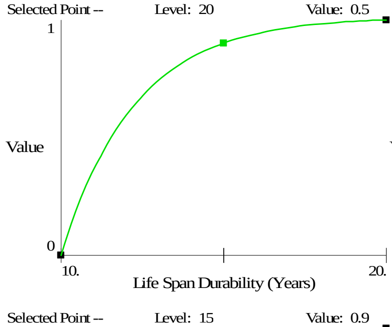
Single Dimension Value Functions:

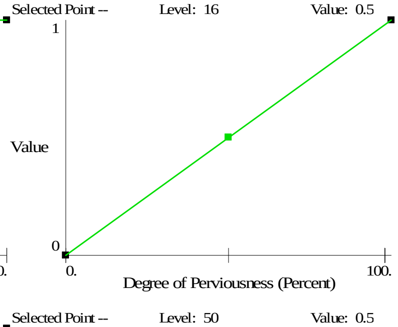


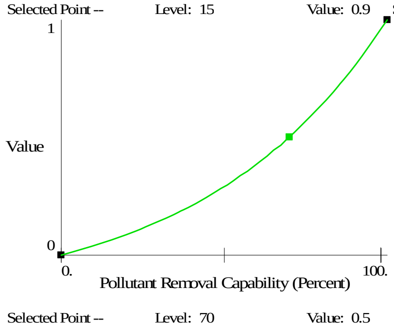












Contractor Experience

Construction Time

Inspection Man-hours

Sweeping Man-hours

Supports SWPPP

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Vita

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First Lieutenant Bulson's first assignment was with the 718th Civil Engineer Squadron, Kadena Air Base, Japan, where he served as an Environmental Program Manager and a Contract Programmer. While at Kadena, he also deployed to Balad AB, Iraq, for 120 days in support of OPERATION IRAQI FREEDOM. In August 2004, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio. Upon graduation, First Lieutenant Bulson will be returning to Baghdad, Iraq, to serve a 365-day tour with Multi-National Force-Iraq.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
23-03-2006	**Master's Thesis**	Jun 2005 – Mar 2006

4. TITLE AND SUBTITLE Using Value-Focused Thinking to Evaluate the Practicality of Porous Pavement Parking Areas on Air Force Installations	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Bulson, Christopher, D., First Lieutenant, USAF	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT/GEM/ENV/06M-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) HQ AFCEE/ICM Attn: Mr. Scott C. Newquist 3300 Sidney Brooks, Bldg. 532 Brooks City-Base TX 78235-5112 DSN: 240-3517	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Natural runoff processes have been altered by urban development; impervious surfaces (rooftops, highways, parking areas) and their associated stormwater systems channel runoff from a vast area into one concentrated outflow. This stormwater runoff can cause erosion, flooding, landslides, and significant damage to aquatic ecosystems. Runoff from highways and parking areas has also been known to contain high levels of suspended solids, heavy metals and hydrocarbons. Porous pavements allow infiltration of water through typically impervious surfaces, reducing stormwater volumes and acting as a pollutant filtration system.

Since there is currently no methodology for Air Force decision-makers to compare conventional and porous pavements, a model was created using Value-Focused Thinking (VFT) to evaluate different paving options. Four porous paving alternatives were compared against two conventional paving alternatives at three separate geographic locations. These alternatives were scored using a total of 12 evaluation measures that were identified as important to the pavement selection process. Structural turf was found to be the best option for northern tier locations, while conventional asphalt was the best choice for central and southern areas. VFT was also shown to be an effective methodology for comparing conventional and porous paving alternatives, objectively weighing economic costs against environmental considerations.

15. SUBJECT TERMS
Decision Analysis, Value-Focused Thinking, VFT, Porous Pavements, Pavement Selection

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Ellen C. England, Lt Col, USAF (ENV)
REPORT	**ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
U	**U**	**U**	**UU**	117	(937) 255-3636, ext 4711; e-mail: Ellen.England@afit.edu

Standard Form 298 (Rev: 8-98)
Prescribed by ANSI Std. Z39-18